**Washington State
Department of Transportation**

U.S. 101 MP 100.70 Unnamed Tributary (WDFW ID 990730): Preliminary Hydraulic Design Report

Paul DeVries Ph.D., PE, CFP, FPT20-11347
Stream Design Engineer, Fisheries Biologist, Fluvial Geomorphologist
Kleinschmidt Associates

Chiming Huang Ph.D. PE, FPT20-31475
Stream Design Engineer
Kleinschmidt Associates

Andrew Nelson LG, FPT20-36866
Fluvial Geomorphologist
Northwest Hydraulic Consultants

Isha Deo EIT, FPT20- 32443
Stream Design Engineer
Kleinschmidt Associates

Darrell Sofield LG
Fluvial Geomorphologist
Northwest Hydraulic Consultant

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1   Introduction

To comply with United States et al. vs. Washington et al. No. C70-9213 Subproceeding No. 01-1 dated March 29, 2013 (a federal permanent injunction requiring the State of Washington to correct fish barriers in Water Resource Inventory Areas [WRIAs] 1–23), the Washington State Department of Transportation (WSDOT) is proposing a project to provide fish passage at the United States Highway 101 (U.S. 101) crossing of the unnamed tributary (UNT) at Mile Post (MP) 100.70. This existing structure on U.S. 101 has been identified as a fish barrier by the Washington Department of Fish and Wildlife (WDFW) and WSDOT Environmental Services Office (ESO) (site identifier [ID] 990730) and has an estimated 5,715 linear feet (LF) of habitat gain.

Per the injunction, and in order of preference, fish passage should be achieved by (1) avoiding the necessity for the roadway to cross the stream, (2) use of a full-span bridge, or (3) use of the stream simulation methodology. The crossing was evaluated using the unconfined bridge design methodology because the floodplain utilization ratio is greater than 3, and incorporated aspects involving the stream simulation design methodology.

The crossing is located in Grays Harbor County 13 miles north of Hoquiam, Washington, in WRIA 22. The highway runs in a north to south direction at this location and is about 700 feet (ft) upstream of the confluence with an unnamed tributary to South Branch Big Creek. The unnamed tributary of interest for this project generally flows from west to east beginning approximately 6,200 ft upstream of the U.S. 101 crossing (see Figure 1 for the vicinity map).

The proposed project will replace the existing 36-inch-diameter by 103-foot-long reinforced concrete pipe (RCP) with a realigned, oversized 13 feet wide, approximately 114 feet long concrete box structure that will exceed the minimum hydraulic opening required for this site. The proposed structure is designed to meet the requirements of the federal injunction using the unconfined bridge design criteria as described in the 2013 WDFW *Water Crossing Design Guidelines* (WCDG) (Barnard et al. 2013). This design also follows the WSDOT *Hydraulics Manual* (WSDOT 2019) with supplemental analyses as noted.

A draft Preliminary Hydraulic Design (PHD) report was prepared in 2020 by WSDOT and HDR Engineering, Inc. under Agreement Number Y-12374 between HDR and WSDOT Environmental Services Office. WSDOT received review comments on the draft PHD report from Washington Department of Fish and Wildlife (WDFW) and the Quinault Indian Nation (QIN). As part of Kiewit's Coastal-29 Team of the US 101/SR 109 Grays Harbor/Jefferson/Clallam, Remove Fish Barriers Project under a Progressive Design-Build (PDB) contract between Kiewit and WSDOT, Kleinschmidt Associates (KA) reviewed the draft PHD report, updated the hydraulic modeling and design, addressed WDFW and Tribe comments, and prepared this Draft Final PHD report using material in the draft PHD report as a starting point. Responses to WDFW and Tribe comments are included in Appendix J. While HDR's original field observations and measurements, and selected figures have been retained in this report, all writing and analyses in the draft PHD report have been reviewed, edited, and updated where determined necessary.

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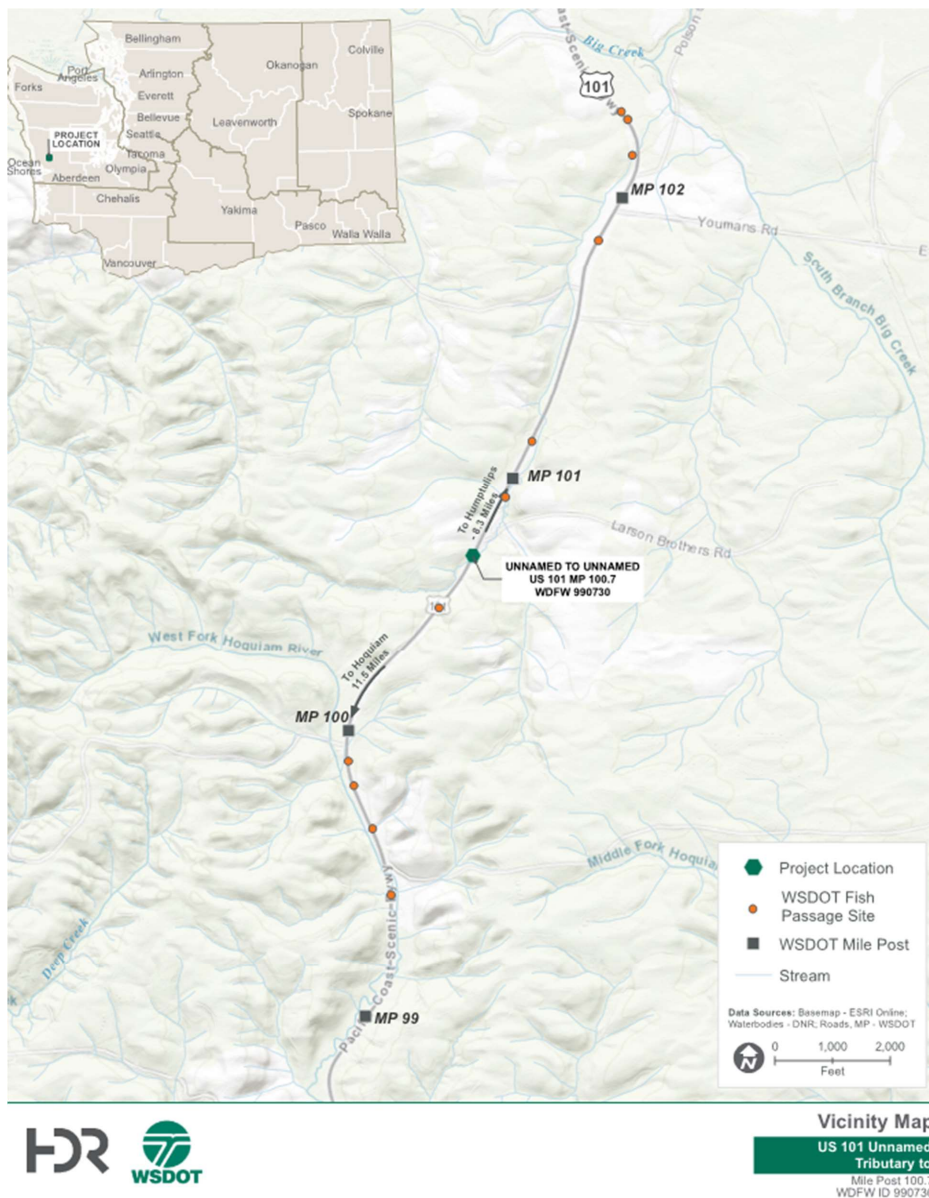
Figure 1: Vicinity map

2 Watershed and Site Assessment

The existing site was assessed in terms of watershed, land cover, geology, floodplains, fish presence, observations, wildlife, and geomorphology. This was performed using desktop research including aerial photos; resources such as the United States Geological Survey (USGS), Federal Emergency Management Agency (FEMA), and WDFW; past records like observation, maintenance, and fish passage evaluation; and site visits.

2.1 Watershed and Land Cover

The project watershed is located within the southern foothills of the Olympic Mountains, approximately 11.7 miles north of Hoquiam, WA. The watershed is generally forested, and the basin is intersected by existing logging roads (Figure 2). The stream is tributary to another unnamed tributary to the South Branch of Big Creek, which joins the Humptulips River and ultimately discharges into Grays Harbor.

Land cover for this basin consists of primarily forest and scrub/shrub land. The 2016 National Land Cover Database (NLCD) map shows land cover to be mostly forested with areas in different stages of regeneration (Figure 2). The Grays Harbor County Assessor's Office web mapping database indicates the stream flows through parcels owned by timber companies. The entire basin has been logged at one time or another and the drainage is intersected by logging roads. A narrow single-lane road network is visible in a Lidar hillshade model that appears to predate US 101 and Larson Bros Road. Roadbeds appear to cross the project stream approximately 390 feet upstream and 590 feet downstream of the culvert. Upstream, the elevated roadbed pulled away from the channel. The downstream crossing lines up with a pronounced cobble grade control riffle. Both crossings appear to be grade controls that create slight inflections in the channel profile. Historic aerial imagery on Google Earth indicates that nearly all of the drainage was clearcut without leaving a riparian buffer strip more than 30 years ago, and that the remaining drainage area was clearcut in the early 2000s, including in what is now treated as the riparian management zone. Future timber harvest is expected to follow Washington's Forest Practices Habitat Conservation Plan requirements involving wider buffer strips than was typical prior to 2005.

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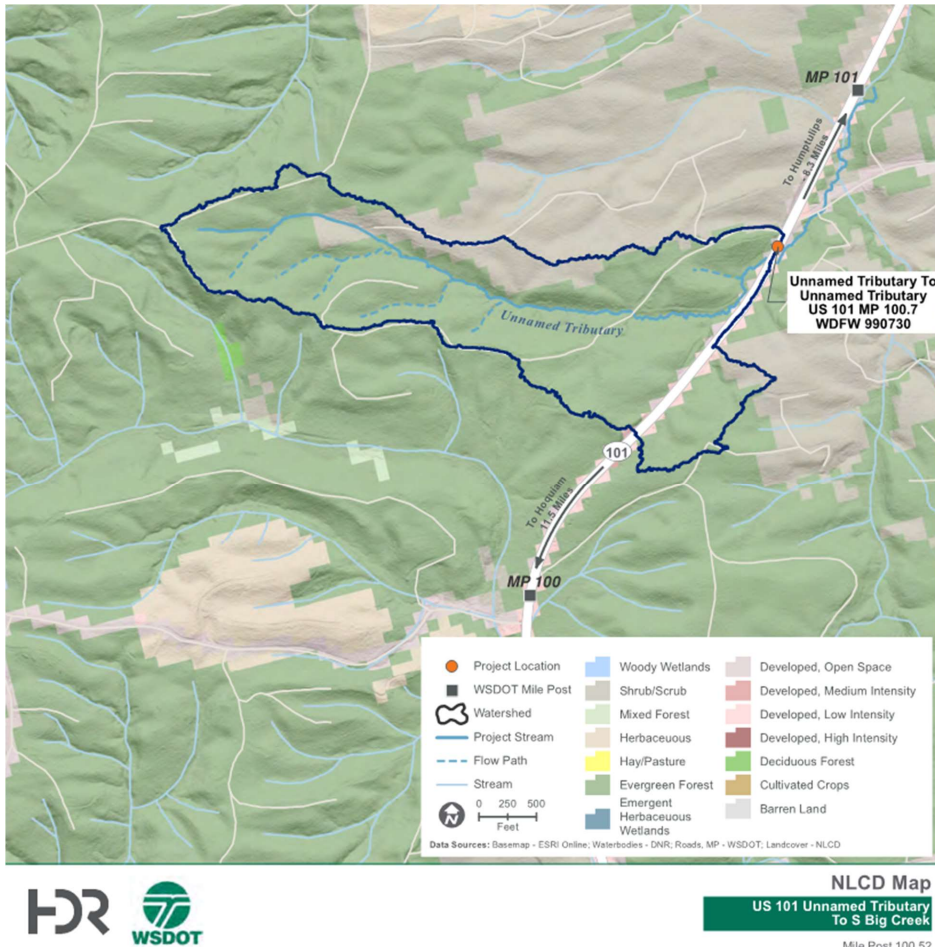
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2.2   Geology and Soils

The drainage basin is underlain entirely by Pleistocene Age, alpine glacial outwash, dated as younger pre-Wisconsinan in age as mapped at the 1:100,000 scale (Logan 2003, Washington State Department of Natural Resources (DNR) 2016). Logan (2003) describes this unit as consisting of sand and gravel, composed of sandstone and basalt derived from the core of the Olympic Mountains. Clasts comprising the deposit are generally moderately to well-rounded with characteristic red-orange weathering rinds. The grainsize distribution of the material is characteristically poorly to moderately sorted and the material is weathered to depths exceeding 12 ft.

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No indicators of landslide activity were observed during the July 13, 2021 field visit. A boundary search conducted August 2021 of the DNR landslide inventories and hazards (Washington Geological Survey, 2020a and 2020b) identified no landslide studies or landslide hazards within the watershed. The watershed's hillslopes are composed almost exclusively of Copalis and Le Bar soil types, which consist of moderately to highly erodible silt loams (Figure 3; NRCS web soil survey).

A weathered sandy silt hardpan was visible in an eroding bank and channel section and similar material is assumed to be found beneath the channel alluvium. Abundant fine sediments in the channel and floodplain may be the remnant signature of logging effects in the basin. Historic logging within the riparian zone likely caused pulses of sediment delivery when land near to the stream was cleared.

Figure 3: Soils map (NRCS Soil Survey Website). An approximate catchment area upstream of the culvert is depicted

2.3   Floodplains

The project is not within a regulatory Special Flood Hazard Area defined as the 1 percent or greater annual chance of flooding in any given year. The existing U.S. 101 culvert is located in Zone X (unshaded) based on FEMA Flood Insurance Rate Map (FIRM) 53027C0470D, effective date February 3, 2017. An unshaded Zone X represents areas of minimal flood hazard from the principal source of flooding in the area and is determined to be outside the 0.2 percent annual chance floodplain.

Maintenance records provided do not describe any historical flooding issues.

2.4 Site Description

The culvert was documented by WDFW to have an estimated 33 percent fish passability because of the steep slope and high velocities in the culvert, and is downstream of an estimated 5,715 feet of habitat

(WDFW 2020). Habitat in the vicinity of the culvert and upstream appears to be suitable for primarily juvenile salmonids, with no spawning habitat found upstream.

The structure has not been identified as a failing structure or with a status of chronic environmental deficiency. No maintenance problems have been noted by WSDOT for this culvert.

2.5 Fish Presence in the Project Area

The project stream is a left bank tributary to another unnamed stream that flows into the South Branch of Big Creek. WDFW SalmonScape and Priority Habitats and Species (PHS) data (WDFW 2020a, 2020b, respectively) show Coho Salmon (*Oncorhynchus kisutch*) in the unnamed tributary downstream of the project reach, and Chum Salmon (*Oncorhynchus keta*) in the lower reaches of the unnamed tributary near the confluence with South Branch Big Creek. Chum salmon do not rear in fresh water very long, and juveniles move out to estuaries soon after emerging from the gravel (Salo 1991). It is therefore unlikely that chum salmon would disperse upstream in the unnamed tributary to the project reach.

Statewide Washington Integrated Fish Distribution (SWIFD) and the PHS data show coastal Cutthroat Trout (*Oncorhynchus clarkii clarkii*) occurring in the project area, both upstream and downstream of the crossing (SWIFD 2020, WDFW 2020b). Coastal cutthroat trout are widespread throughout small streams in Washington and prefer the uppermost portions of these streams, and can be anadromous and rear in streams for 2 to 3 years, or be resident and remain entirely in fresh water (Wydoski and Whitney 2003). A small salmonid (approximately 3 inches [in] long) that was potentially a coastal cutthroat trout was observed near the culvert outlet during the field survey on May 18, 2020.

Steelhead (*Oncorhynchus mykiss*) are documented in the South Branch of Big Creek by WDFW (2020a), and the PHS database indicates the presence of rainbow trout, the resident form of steelhead as present in the unnamed tributary downstream of the project crossing (WDFW 2020b). Steelhead that inhabit the watershed are part of the Olympic Peninsula distinct population segment and are not currently listed under the Endangered Species Act (ESA). The WDFW online fish passage does not list any impassable barriers on the unnamed tributary between the confluence of South Branch Big Creek and upstream where the project is located (WDFW 2019). Rearing and overwintering juvenile steelhead may potentially disperse upstream to reaches close to the project crossing.

Table 1 provides a list of fish species that occur in the study area in the unnamed tributary and that would be affected by the culvert crossing.

Table 1: Native fish species potentially present within the project area

Species	Presence (presumed, modeled, or documented)	Data source	ESA listing
Coho salmon (*Oncorhynchus kisutch*)	Documented downstream	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted

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Species	Presence (presumed, modeled, or documented)	Data source	ESA listing
Steelhead (*Oncorhynchus mykiss*)	Presumed (documented in Big Creek)	SWIFD 2020, WDFW 2020a, WDFW 2020b	Not warranted
Coastal cutthroat (*Oncorhynchus clarkii clarkii*)	Documented	SWIFD 2020, PHS	Not warranted

2.6 Wildlife Connectivity

The one-mile segment that the US 101 MP 100.70 unnamed tributary crossing falls in the category of low priority for Ecological Stewardship and low priority for Wildlife-related Safety. The adjacent segment to the north ranked high for Ecological Stewardship and low for Wildlife-related Safety, and the segment to the south ranked low for Ecological Stewardship and medium for Wildlife-related Safety. At this time, WSDOT has not identified this site as a Wildlife Connectivity Investment Priority. Therefore, no habitat connectivity analysis is performed for this site.

2.7 Site Assessment

A site assessment was performed characterizing fish habitat, hydraulic and geomorphic conditions, and the culvert based on field visits, WDFW's barrier inventory report (WDFW 2020), and a WSDOT survey. An initial visit occurred in 2020, with subsequent visits postponed until 2021 after the Covid-19 pandemic had begun to subside.

2.7.1 *Data Collection*

Site visits were performed on four occasions to collect data and observe conditions and characteristics influencing the hydraulic design:

- HDR visited the project site on May 18, 2020, to collect pertinent information to support development of an initial design, including bankfull width (BFW) measurements, and characterizations of instream fish habitat and floodplain conditions. Channel substrates, large wood accumulations and floodplain vegetation were characterized.
- Kleinschmidt-R2 and Kiewit visited the site on June 1, 2021 to corroborate the initial data collection findings, review the representativeness of the BFW and channel substrate measurements, and identify additional data collection needs.
- Kleinschmidt-R2 and Kiewit visited the site on June 15, 2021 to collect a bulk substrate sample, measure the hydraulic effect of natural downstream in-channel flow obstructions as it would affect hydraulic modeling predictions, and measure the typical size of mobile wood pieces upstream of the culvert as they would affect the determination of minimum freeboard requirements.

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The one-mile segment that the US 101 MP 100.70 unnamed tributary crossing falls in the category of low priority for Ecological Stewardship and low priority for Wildlife-related Safety. The adjacent segment to the north ranked high for Ecological Stewardship and low for Wildlife-related Safety, and the segment to the south ranked low for Ecological Stewardship and medium for Wildlife-related Safety. At this time, WSDOT has not identified this site as a Wildlife Connectivity Investment Priority. Therefore, no habitat connectivity analysis is performed for this site.¶
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- Kleinschmidt-R2 and NHC visited the site on July 13, 2021 to support an evaluation of the long term vertical stability of the channel.

Field reports are presented for each visit in Appendix B.

WSDOT also surveyed the site in March 2020. The survey extended approximately 250 feet upstream of the culvert, 240 feet of channel downstream of the culvert, and a total roadway survey length of approximately 1,500 feet.

2.7.2 *Existing Conditions*

2.7.2.1 *Culvert*

The existing structure is a 103 feet long, 36-inch diameter round concrete pipe with a gradient of approximately 0.7 percent according to WSDOT survey data. This differs from the 1.3 percent estimate made by WDFW (2020) in the barrier survey and is assumed to be more accurate because it was surveyed to datum. The culvert runs perpendicular to the road instead of within the historic channel footprint, which appears to have run diagonally to the road layout, at an approximately 42 degree angle from perpendicular to the road. A review of the light detecting and ranging (LiDAR) data suggests that the channel was relocated to accommodate a shorter culvert, which involved excavation a channel on the downstream side to connect with the historic channel where it flows away from the road prism. The historic channel appears to have been filled, and a new channel partially excavated downstream of the culvert along the base of the road prism (see Section 2.8). Roadway posts placed on the left banks just upstream of the culvert are catching debris and holding material on the banks (Figure 4). Downstream of the roadway posts, the channel takes a hard 90-degree right turn to enter the culvert. The culvert inlet projects from the roadway fill with a 4-5 feet long section broken off (Figure 5). The culvert outlet projects from the road fill and has a clean bottom (Figure 6). The channel takes a 90-degree turn below the outlet and appears to have been excavated into hardpan for conveyance back to where the historic channel leaves the road (Figure 7).

Figure 4: Looking downstream at roadway posts on the left bank above the culvert inlet

Figure 5: Culvert inlet with broken segment

Figure 6: Culvert outlet

Figure 7: Looking downstream of the culvert outlet

2.7.2.2   Stream

The reach upstream of the culvert flows through a densely vegetated, immature wooded floodplain with extensive patches of wetlands vegetation. Small woody material is present in abundance forming debris jams and steps (Figure 8), with some pieces of remnant large woody material (LWM) also present. The channel substrate is predominantly fine sand and silt, with sparse small gravel heavily embedded with fines and concentrated in pockets (Figure 9). The channel bottom is soft and plane bed in profile, with

easily erodible banks that are approximately 1.0 to 2 feet high, and fine sediments are present in large deposits (Figure 10).

The downstream reach can be characterized as three sequential sub-reaches with different channel types. The excavated section below the culvert is highly confined with steep walls as it runs parallel to U.S. 101 for approximately 125 feet. There is little habitat complexity in this subreach. The banks and channel within this section are both hardpan material. The channel is fairly shallow, around 0.5 foot deep. Stream bank height varies from 4 to 7 feet (Figure 11). The channel meanders away from the road prism between two older Douglas Fir (*Pseudotsuga menziesii*) trees and the floodplain opens up with large patches of wetlands vegetation. The two older trees appear to bracket where the historic channel planform ran under the present highway's footprint. The channel is less confined, with more woody material, small step pools, flow splits, and logs and rootwads (Figures 12-15). Substrates include gravel downstream of steps, and extensive deposits of sand and small gravel (Figure 16). Farther downstream where the channel abuts Larson Brothers Road, there is a distinct cobble bedded grade control (Figure 17).

Figure 8: Example of small woody material in channel

Figure 9: Representative gravel streambed material upstream of culvert

Figure 10: Example of erodible banks and large fines deposits along channel upstream of culvert

Figure 11: Typical excavated channel section downstream of culvert outlet

Figure 12: Representative view of unconfined channel downstream of the culvert

Figure 13: Representative woody material within the unconfined section downstream of the culvert

Figure 14: Flow split within the unconfined section downstream of the culvert

Figure 15: Looking downstream at a rootwad within the unconfined section downstream of the culvert

Figure 16: Typical streambed material in unconfined reach downstream of culvert

Figure 17: Cobble grade control downstream of unconfined reach below culvert

2.7.2.3   Floodplain

The floodplains upstream and downstream of the culvert are low in elevation relative to the channel and appear to be hydrologically connected during more frequent flood events where the stream does not run along the base of the road prism. A bankfull channel profile is distinct (Figure 18). The floodplains are vegetated with a mix of riparian and wetlands trees, shrubs, sedges, and other genera. The material forming the floodplains is soft silt and sand, and may be a legacy of historic clearcutting of the riparian zone.

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Deleted: Figure 17: Cobble grade control downstream of unconfined reach below culvert¶

2.7.3 *Fish Habitat Character and Quality*

Upstream of the U.S. 101 crossing, the unnamed tributary flows through a predominantly deciduous forest consisting primarily of alder (*Alnus rubra*). Farther upstream, to the west of the surveyed reach, the tree cover becomes a uniform stand of young Douglas fir as part of a timber harvested area. There is a dense shrub understory with native species including salmonberry (*Rubus spectabilis*), willows (*Salix spp.*), vine maple (*Acer circinatum*), and sword fern (*Polystichum munitum*). The mature forest and shrub cover provides good shading, nutrient inputs, and some potential for LWM recruitment. LWM is important in western Washington streams in that it provides cover for fish and contributes to stream complexity, which is beneficial to salmonids.

There were few pieces of LWM in the upstream reach, but smaller woody material such as branches and stems is prevalent. There were three places where logs and woody material were present in the stream channel and banks, and a total of nine key pieces of LWM. These logs ranged from 6 to 12 inches in diameter. Much of the LWM constituted several debris jams of small branches and twigs near the downstream end of the reach, but provide little instream habitat function such as creating pools and cover.

The upstream reach near the culvert inlet was heavily overgrown with shrubs and the channel was poorly defined. Farther upstream the channel becomes defined with low, incised banks. Instream habitat is predominantly shallow glide with fines and hardpan in the substrate throughout the reach. Pool habitat was lacking throughout the upstream reach. There is a small scour pool undercut of the right bank and tree roots. The lack of pools and instream habitat complexity does not provide good rearing habitat, but juvenile coho and possibly juvenile steelhead could use the stream for some rearing and overwintering habitat, particularly during higher flows in the larger streams downstream.

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Downstream of the U.S. 101 crossing, the unnamed tributary flows through a predominantly deciduous forest consisting primarily of alder, with some Douglas fir and western hemlock (*Tsuga heterophylla*) primarily up the hillslope on the right bank. The forested riparian corridor is constrained on the left bank of the stream because of its proximity to the highway. There is a dense shrub understory with native species including salmonberry, willows, vine maple, sword fern, and lady fern (*Athyrium filix-femina*). The mature forest and shrub cover provides good shading, nutrient inputs, and some potential for LWM recruitment.

The downstream reach had very few pieces of key LWM. Much of the LWM consisted of branches and smaller woody debris including three small debris jams that created small hydraulic drops of a few inches at the downstream end of the reach (Figure 18). There were three places where logs and woody material were present in the stream channel and banks, and a total of five key pieces of LWM. These logs ranged from 4 to 18 inches in diameter. Near the upstream end where the banks were incised, in two places, large conifer logs lie across the bankfull channel well above the wetted stream, and have little instream habitat influence.

The substrate in the downstream reach is almost entirely composed of fines, including areas of clay and hardpan. This instream habitat is not suitable for spawning for salmonid species, but does provide some rearing and migratory habitat. There is little instream habitat complexity, and pools and cover are lacking in the downstream reach. There was one small scour pool along the right bank where the bank and some tree roots were undercut. The lack of pools and instream habitat complexity does not provide good rearing habitat, but the reach still provides migratory habitat and some rearing habitat, particularly as refuge during winter high flows in the larger streams downstream.

2.8   Geomorphology

Geomorphic information provided for this site includes selection of a reference reach, the basic geometry and cross sections of the channel, stability of the channel both vertically and laterally, and various habitat features.

2.8.1   *Reference Reach Selection*

A reach starting approximately 130 feet upstream of the culvert (Figure 19) was selected as most representative of the natural stream channel with the least anthropogenic influence, and is situated in line with the larger scale reach grade (see Section 2.8.4). The reference reach was relied on primarily for measuring bankfull dimensions for informing the design of the hydraulic opening width and the cross-section morphology of the constructed channel outside of the replacement structure footprint. The reference reach morphology was not used to design cross-section shape and planform underneath the replacement structure because vegetation controlling bank stability cannot generally grow there.

Figure 19: Reference reach and locations of BFW measurements and substrate sampling

2.8.2 Channel Geometry

The project stream flows through a confined valley that is eroded into weathered silty sand hardpan, and further confined by fill associated with the roadbeds of US 101 and private timber roads. The channel planform meanders with a low sinuosity both upstream and downstream of the existing culvert. The channel is single thread and does not vary significantly in width, except where it is split by the occasional piece of instream wood. In the upstream area, the channel cross-section is narrow, shallow, and generally unconfined (Figure 18). Water flows for approximately 125 feet along the base of the road prism downstream of the culvert in what appears to have been an elevated, excavated and highly confined channel. Farther downstream, the channel flows away from the road prism between two large, older conifers that appear to demarcate the location of the historic channel. The channel becomes shallow again and expresses greater engagement with a low relief floodplain. The channel morphology is

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judged to be generally stable, consistent with Stage I of Schumm et al.'s (1984) Channel Evolution Model.

Bankfull width (BFW) was measured with tape at three locations, two upstream and one downstream of the culvert (Figures 20-22). The measured BFWs resulted in a design average BFW of 8.0 feet, which is consistent with independent QIN and WDFW measurements (Table 2). As an independent check, the BFW estimate based on the WCDG regression equation for high-gradient, coarse-bedded streams in western Washington was 8.2 feet, based on the basin area and mean annual precipitation (see Section 3; Barnard et al. 2013).

WSDOT also surveyed cross sections at three other locations upstream of the culvert as part of data collection for developing the hydraulic models, where Station (STA) 55+02 is located within the reference reach (Figure 23). Channel BFWs are around 9 ft or less. For the 100-year event, the width:depth ratio is 2.4.

Table 2: Bankfull width measurements

BFW #	Width (ft)	Included in Average	Concurrence notes
1	9.0 ft	Yes	
2	7.3 ft	Yes	
3	7.0 ft	Yes	
Average	8.0 ft		Agreed by QIN and WDFW on May 24, 2021

Figure 20: Location of downstream BFW measurement

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Figure 21: Location of upstream BFW measurement #2

Figure 22: Location of upstream BFW measurement #3
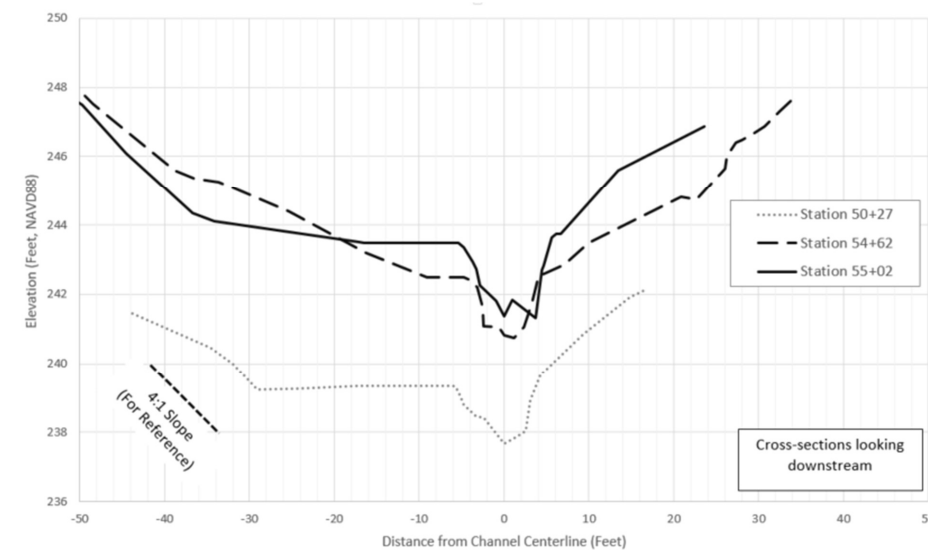
Figure 23: WSDOT's surveyed cross-section profiles upstream of the culvert

2.8.3 Sediment

Most of the streambed is composed of sand and silt, with patches of gravel present. The stream appears to be gravel limited overall. A pebble count was performed of a patch within the reference reach during the May 2020 site visit, and a second pebble count was performed at the downstream cobble grade control in 2021 that may have been an artifact of historic logging road construction (Figure 19; Table 3). The 2020 pebble count was completed using a gravelometer to measure 123 stones; the 2021 pebble count was performed using a ruler and measured 100 stones at the cobble grade control downstream of the project reach. The results of the pebble count within the reference reach indicated that gravel patches in the streambed are composed primarily of fine to medium gravel and coarse sand. The largest sediment size observed upstream of the grade control was 2.0 inches in diameter. The cobble grade control grain size distribution is considered to be indicative of an immobile substrate in the project reach.

Table 3: Pebble count results

Particle size	Reference Reach Diameter (in)	Reference Reach Diameter (mm)	Grade Control Diameter (in)	Grade Control Diameter (mm)
D_{16}	0.1	2.5	2.5	64
D_{50}	0.2	5.0	3.6	92
D_{84}	0.5	13	4.5	115
D_{95}	0.8	20	5.4	138
D_{100}	2.0	51	7.3	185

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2.8.4 *Vertical Channel Stability*

A long channel profile was developed from 2020 survey data and LiDAR data (USGS and Quantum Spatial 2019). The LiDAR data consisted of a bare earth digital elevation model provided in a raster format with a horizontal resolution of 3 feet and a vertical accuracy of 0.271 foot. The long channel profile (Figure 24) describes slopes approximately 2,200 feet upstream and downstream from the project culvert and includes major landmarks along the tributary. As will be seen in the design plans (Appendix E), the upstream and downstream reaches are approximately in grade with each other where the stream channel used to flow prior to realignment. Nonetheless, despite the channel realignment that occurred, field observations do not indicate recent vertical channel instability either upstream or downstream of the crossing, suggesting little potential for future vertical adjustment. The location of the cobble bar downstream grade control further promotes grade stability in the project reach, and likely predates the road construction of the US 101 and Larson Brothers Road crossings. The slope calculated between the upstream and downstream grade controls is 1.12%. Excluding the channel realignment, the profile downstream is 1.11%, and upstream is 1.35%. Large wood steps support these slopes, and maintenance of such slopes will require continued recruitment of large wood to the channel in the future.

The maximum extent of aggradation and degradation that are expected over an engineering timescale depends on the relative rates of the two processes. Our assumption is that land use in the watershed caused rates of aggradation greater than what we would expect in the future, for several reasons. First, the potential of landslides or debris flow type sediment delivery is low in the watershed given the prevailing relief. Historical clearcut logging including within the riparian zone likely created spikes in sediment supply and increased runoff greater than would be expected in the future after the 2005 change in forest practices rules. Despite these extremes, we see no physical field evidence of large-scale aggradation or degradation within the observed reach, and there are various buried log steps in the channel that help maintain grade in addition to the cobble section downstream. The cobble grade control downstream provides mitigation against larger-scale degradation overall.

And, noting that the proposed culvert is not significantly longer than the existing culvert, realignment of the stream channel back to its likely historic course can be projected to shorten the profile in Figure 24 by about the length of the excavated section. The essentially parallel grades upstream of the cobble grade control and above US 101 depicted in Figure 24 then become approximately superimposed on each other, indicating that the overall grade has remained stable despite the historic realignment that occurred.

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Figure 24: Watershed-scale longitudinal profile (NAVD88 datum); Red dashed lines indicate approximately parallel reach scale grades upstream and downstream of US 101 that were offset by construction of the existing culvert

2.8.5 *Channel Migration*

Channel migration was assessed based on topography and field observations. The stream is too small and canopy too thick for aerial photography to be of use for evaluating migration history. Hydraulic modeling indicates the floodplain upstream and downstream of the modified sections of channel are inundated at the 2-year recurrence interval event. However, the stream is not highly sinuous and did not exhibit signs in the field of significant channel meandering or avulsion, with the planform constrained by dense vegetation upstream, and the adjacent hillside, LWM, and mature riparian trees downstream of the modified section. These are typically mitigating factors against channel migration in a stream with the prevailing steep slope and small channel size. Additionally, the historic channel grades are relatively uniform upstream of the cobble grade control, and thus there appears to be a low risk of future destabilization of the channel laterally that might otherwise be associated with a change in grade due to larger scale sedimentation or erosion.

2.8.6 *Riparian Conditions, Large Wood, and Other Habitat Features*

Riparian and floodplain vegetation is dense upstream of the culvert, and the floodplain is also forested. The riparian corridor is predominantly deciduous forest consisting primarily of alder. Farther upstream to the west of the surveyed reach, the tree cover transitions to a uniform stand of young Douglas fir within a prior timber harvest area. There is a dense shrub understory with native species including salmonberry, willows, vine maple, and sword fern. The mature forest and shrub cover provides good shading, nutrient inputs, and some potential for LWM recruitment.
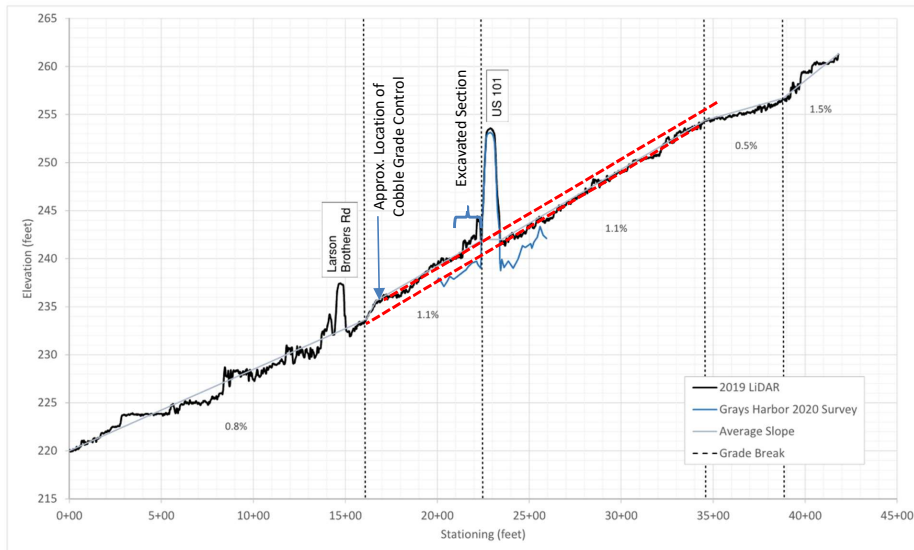
Deleted: Figure 24: Watershed-scale longitudinal profile (NAVD88 datum); Red dashed lines indicate approximately parallel reach scale grades upstream and downstream of US 101 that were offset by construction of the existing culvert¶
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There were few pieces of LWM in the upstream reach, but there is a significant amount of small woody material. The small woody material covers the channel in the lower portion of the reach near the culvert inlet, and also causes small steps and debris jams within the channel. There are a few locations with LWM along the banks and in the overbanks. The lack of LWM within the channel means there are no pools created, changing flow direction, or creating dams, and instream habitat complexity is low. A survey upstream of the culvert did not find any significant pieces of mobile wood, just brush and small twigs. This may reflect the species composition and immature state of the regenerating forest presently, where large branches from evergreen trees are generally absent. Otherwise, trees that fall into or across the channel were observed to remain in place.

Downstream of the crossing a confined reach has steep banks near the culvert outlet. The streambanks become low and poorly defined at the downstream end of the surveyed reach, where some wetland vegetation occurs along the channel margins. The riparian corridor is predominantly deciduous forest consisting of alder, with some Douglas fir and western hemlock primarily up the hill slope on the right bank. The forested riparian corridor is constrained on the left bank of the stream because of its proximity to the highway. There is a moderately dense shrub understory with native species including salmonberry, willows, vine maple, and ferns.

The downstream reach had very few pieces of key LWM. Much of the LWM consisted of branches and smaller woody debris including three small debris jams that created small hydraulic drops of a few inches at the downstream end of the reach. The left floodplain is composed of shrubs and small forest growth while the right floodplain consists of mature forest. Farther downstream, the stream becomes unconfined with wetlands in the left floodplain. Small woody material is abundant and there is also scattered LWM, consisting of large conifer logs spanning above the bankfull channel and isolated rootwads (e.g., Figure 15).

WDFW completed a physical survey in 2005 at the site (WDFW 2005). Beaver dams were observed upstream and downstream of the crossing. Beavers were actively using the reach upstream and downstream of the crossing at the time. Beaver dams and activity were not observed during any of the site visits.

3   Hydrology and Peak Flow Estimates

The project stream drains an ungaged basin, with no long-term historical flow data available. No hydrologic studies, models, or reports were found that summarized peak flows in the basin. Consequently, USGS regression equations (Mastin et al. 2016; Region 4) were used to estimate peak flows at the U.S. 101 crossing. Inputs to the regression equation included basin size and mean annual precipitation. The unnamed tributary has a basin area of 0.22 square mile and a mean annual precipitation within the basin of 105 inches (PRISM Climate Group 2019). The catchment was delineated from LiDAR data acquired from the Washington State Department of Natural Resources (DNR) LiDAR Portal (USGS and Quantum Spatial 2019) using Arc Hydro.

The resulting regression estimates (Table 4) were evaluated for potential sub-regional bias by comparing regression predictions against estimates derived at selected stream gages in the area using available flow records. A Washington Department of Ecology gage was identified from the Wishkah River, but only USGS gages were found with a sufficiently long period of record (>20 years) in the area to permit evaluating the larger predicted flood peaks (Table 5).

Table 4: USGS regression-based estimates of peak flow

Mean recurrence interval (MRI) (years)	USGS regression equation (Region 4) (cfs): design Flows for this crossing	USGS regression standard error (percent)
2	22.6	52.5
10	38.8	50.5
25	46.6	51.7
50	52.8	52.9
100	59.6	54.2
500	73.4	58.0
2080 predicted 100	69.4	NA

Table 5: Local USGS gages used to evaluate bias in USGS regression predictions

Station #	Gage Name	Years of Record
12039005	Humptulips River Below Hwy 101	2002-2018
12036000	Wynoochee River Above Save Creek Near Aberdeen, WA	1952-2018
12035500	Wynoochee River At Oxbow Near Aberdeen, WA	1925-1952
12035450	Big Creek near Grisdale, WA	1972-1996
12035400	Wynoochee River near Grisdale, WA	1965-2018
12039050	Big Creek near Hoquiam, WA	1949-1970
12039100	Big Creek Tributary near Hoquiam, WA	1949-1968

Peak flow data were analyzed for each gage following the Bulletin 17B methodology for peak flow frequency analysis, using the Hydraulic Engineering Center's Statistical Software Package (HEC-SSP) version 2.2. HEC-SSP uses the Log Pearson Type III distribution for annual peak flows on unregulated streams, fit by the Method of Moments. Distribution parameters were estimated for the 2-, 10-, 100-, and 500-year return intervals based on moments of the sample data (site-specific). Adjustments were made for non-standard data, low outliers, and historical events. The resulting peak flow estimates were compared against the regression estimates using the equations in Mastin et al. (2006), where drainage area and mean annual precipitation estimates were determined using USGS' StreamStats web application. The ratio of gage-based to regression-based estimates was then plotted against drainage area (Figure 25). The results indicate that the regression estimates for smaller basins may be generally comparable to or higher than would be derived using gage data. As corroboration, a modeling exercise performed for Culvert ID 993704 using the MGS Flood model indicated that the regression estimates for a similarly sized, nearby drainage area were higher than values estimated based on a more direct simulation of stormwater rainfall-runoff processes. The regression estimates accordingly appear to be more conservative.

Consequently, the regression estimates in Table 4 were used in design development, to provide a safety factor when designing for flood conveyance, freeboard, channel stability, and scour.

Summer low-flow conditions are unknown and high/low fish passage design flows are not included in this analysis. The stream was observed to still be flowing in mid-August 2021.
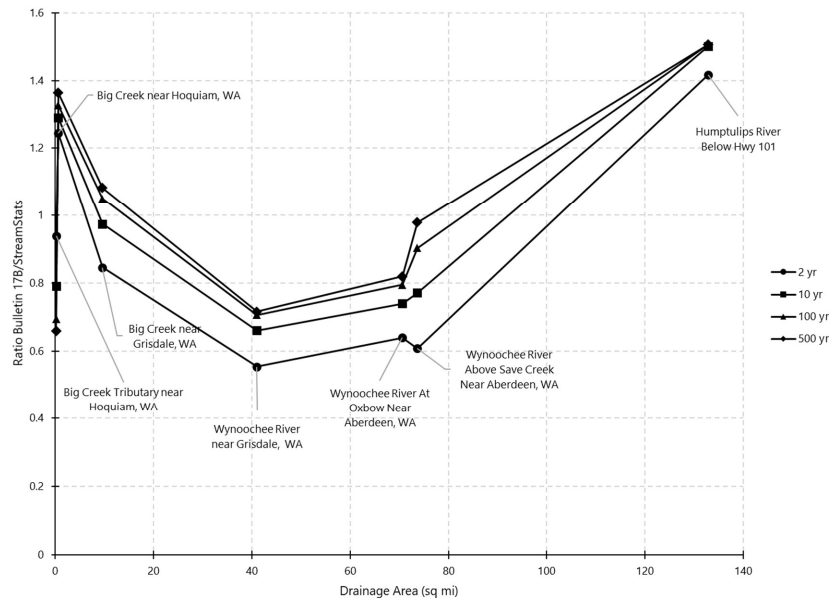

Figure 25: Ratio of gage-based flood peak magnitudes vs. regression-based estimates, plotted against drainage area

4 Hydraulic Analysis and Design

The hydraulic analysis of the existing and proposed U.S. 101 unnamed tributary crossing was performed using the United States Bureau of Reclamation's (USBR's) SRH-2D Version 3 computer program, a two-dimensional (2D) hydraulic and sediment transport numerical model (USBR 2017). Pre- and post-processing for this model was completed using SMS Version 13.1.11 (Aquaveo 2021).

Three scenarios were analyzed for determining stream characteristics of the unnamed tributary with the SRH-2D models: (1) existing conditions with the 36-inch-diameter RCP, (2) estimated natural conditions with the roadway embankment removed, and (3) future conditions with the proposed 13-foot hydraulic opening.

4.1 Model Development

This section describes the development of the model used for the hydraulic analysis and design.

4.1.1 *Topographic and Bathymetric Data*

The channel geometry data in the model were obtained from the MicroStation and InRoads files supplied by the Project Engineer's Office (PEO), which were developed from topographic surveys performed by WSDOT prior to March 13, 2020. The survey data were supplemented with LiDAR data (USGS and Quantum Spatial 2019). Proposed channel geometry was developed from the proposed grading surface originally created by HDR and later updated by Kleinschmidt. All survey and LiDAR information is referenced to the North American Vertical Datum of 1988 (NAVD88) using U.S. Survey feet.

4.1.2 *Model Extent and Computational Mesh*

The upstream extents of the hydraulic model begin about 250 feet upstream of the existing crossing, at the farthest point upstream that has detailed survey data. The downstream extents of the hydraulic model end about 240 feet downstream of the existing culvert, at the limit of detailed survey data. A sensitivity analysis was performed at the downstream boundary condition. The downstream model extents are located a distance downstream such that the model results at the existing and proposed culvert are not influenced by the boundary condition. The survey data are augmented with LiDAR to provide adequate terrain data in the overbanks and coverage at the location of the proposed stream alignment.

The computational mesh elements are a combination of patched (quadrilateral) and paved (triangular) elements, with finer resolution in the channel and larger elements in the floodplain. The existing mesh covers a total area of 58,596 SF, with 5,056 quadrilateral and 28,483 triangular elements (Figure 26). The natural-conditions mesh covers a total area of 58,596 SF, with 3,720 quadrilateral and 21,893 triangular elements (Figure 27). The proposed mesh covers a total area of 51,936 SF, with 4,272 quadrilateral and 17,968 triangular elements (Figure 28).
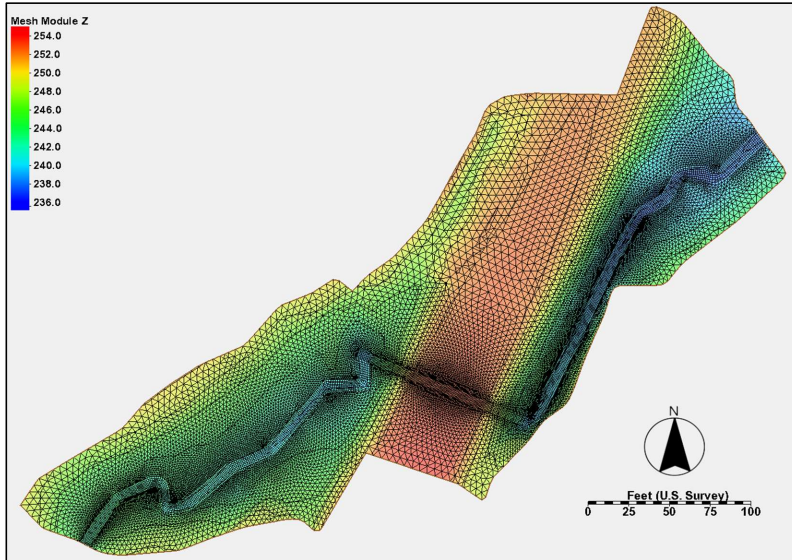
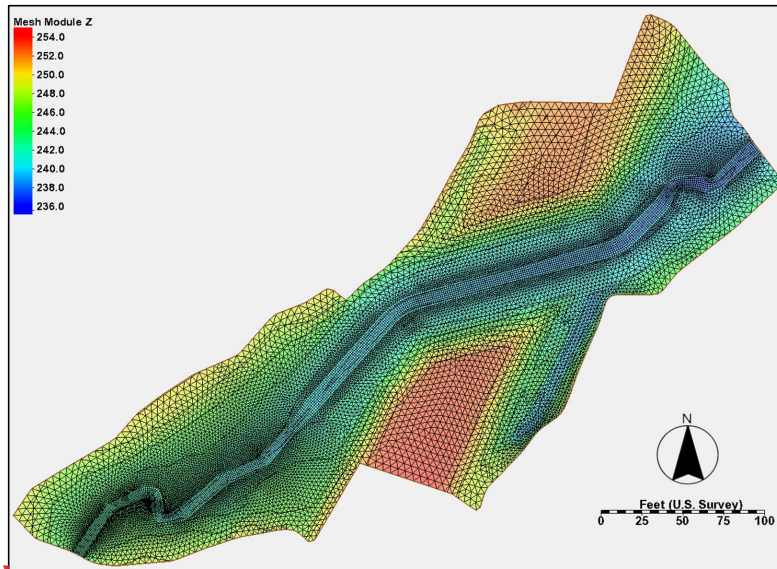**Figure 26: Existing-conditions computational mesh with underlying terrain**

Figure 27: Natural-conditions computational mesh with underlying terrain
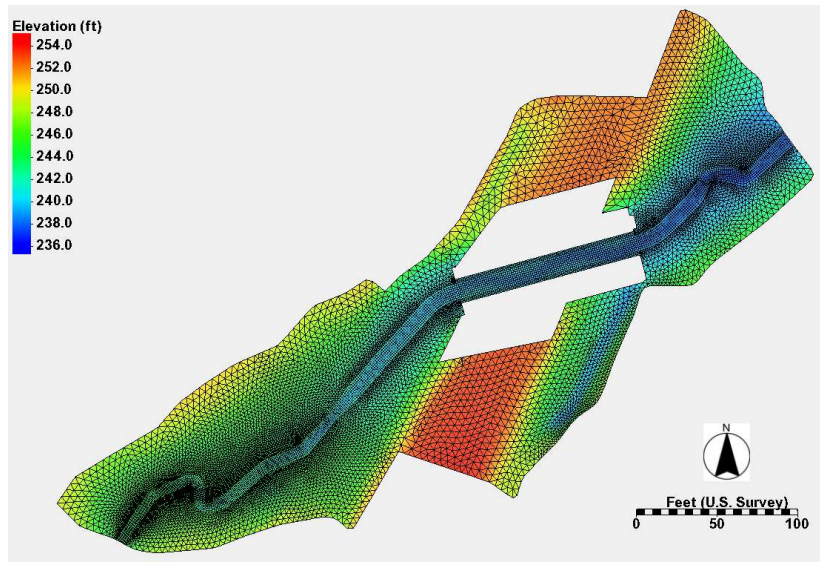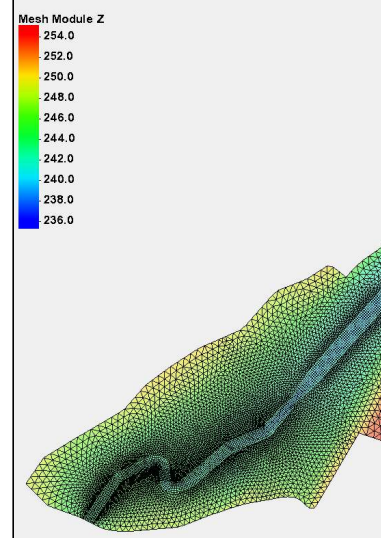
Figure 28: Proposed-conditions computational mesh with underlying terrain

4.1.3 *Materials/Roughness*

Manning's n values were estimated for the natural channel and floodplain of the project stream using the Cowan method based on site observations (Arcement and Schneider 1989; see Appendix G). The resulting values were consistent with standard engineering values for 1-D simulations (Barnes 1967). Because bank stabilizing vegetation is not expected to grow inside the structure, the channel there will have a dominant bed material composed of gravel and small cobble. The value for the culvert was estimated using the same reference, with a base value of n=0.035 for a gravel-cobble mix, and with 0.01 added to account for low profile bedforms that will be part of the final design (see Section 4.4). The resulting 1-D values were then adjusted down by 10 percent to reflect generally expected reductions when moving to a 2-D model parameterization (Robinson et al. 2019; Table 6). Figures 29-31 depict the model spatial distributions of hydraulic roughness coefficient values for existing, natural, and proposed conditions, respectively.

Table 6: Manning's n hydraulic roughness coefficient values used in the SRH-2D model

Land cover type	Manning's n
Channel	0.079
Within Proposed Crossing	0.041
Floodplains	0.111
Roadway	0.020

Manning's n Values
- Channel (0.079)
- Overbank (0.111)
- Road Prism (0.02)

Feet (U.S. Survey)
0   100   200

Figure 29: Spatial distribution of roughness values in SRH-2D existing-conditions model

Manning's n Values
- Channel (0.079)
- Overbank (0.111)
- Road Prism (0.02)

Feet (U.S. Survey)
0   50   100   150

Figure 30: Spatial distribution of roughness values in SRH-2D natural-conditions models

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Manning's n Values
- Channel (0.088)
- Overbank (0.124)
- Road Prism (0.02)

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Figure 31: Spatial distribution of roughness values in SRH-2D proposed-conditions models

4.1.4 *Boundary Conditions*

Model simulations were performed using constant discharges ranging from the 2-year to 500-year peak flow events summarized in Section 3. A constant flow rate was specified at the upstream external boundary, while a normal depth rating curve was used to specify a flow dependent water surface elevation at the downstream boundary. The downstream normal depth boundary condition rating curve (Figure 32) was developed within SMS using the existing terrain, a downstream slope of 1.1 percent read off the longitudinal profile from Figure 24 and a composite roughness of 0.10. The locations of each boundary condition for the existing, natural, and proposed conditions are shown in Figures 33-35, respectively. Model simulations were run for a sufficiently long duration until the results stabilized across the model domain.

An HY-8 internal boundary condition was specified in the existing-conditions model to represent the existing circular concrete culvert crossing (Figure 36). The existing crossing was modeled as a 3-foot-diameter circular pipe within HY-8. A Manning's roughness of 0.012 was assigned to the culvert. The culvert was assumed to be unobstructed and free from any stream material within the barrel.

Figure 32: Downstream normal depth rating curve

Exit H
WSE:Q Rating Curve

U/S Culvert

D/S Culvert

Inlet Q
Constant Flow

Feet (U.S. Survey)
0   25   50   75   100
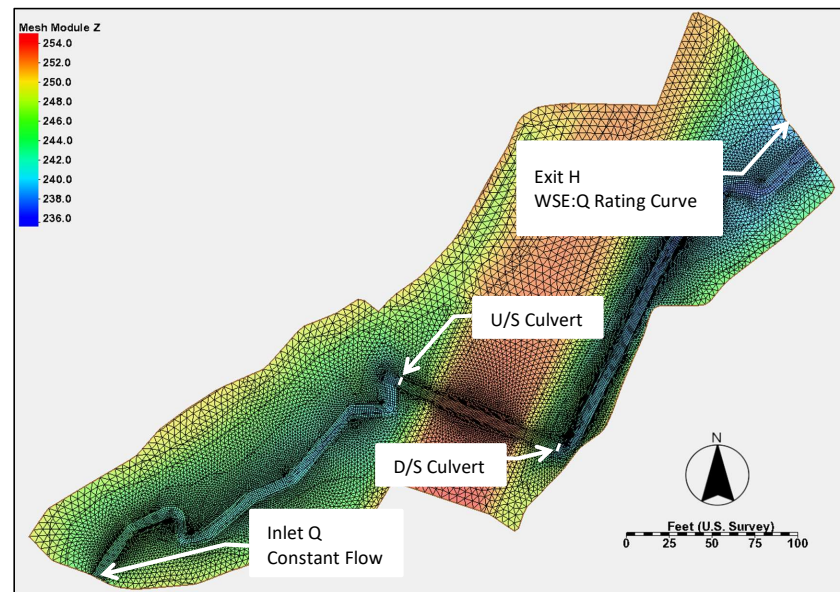
Figure 33: Location of boundary conditions for the existing-conditions model

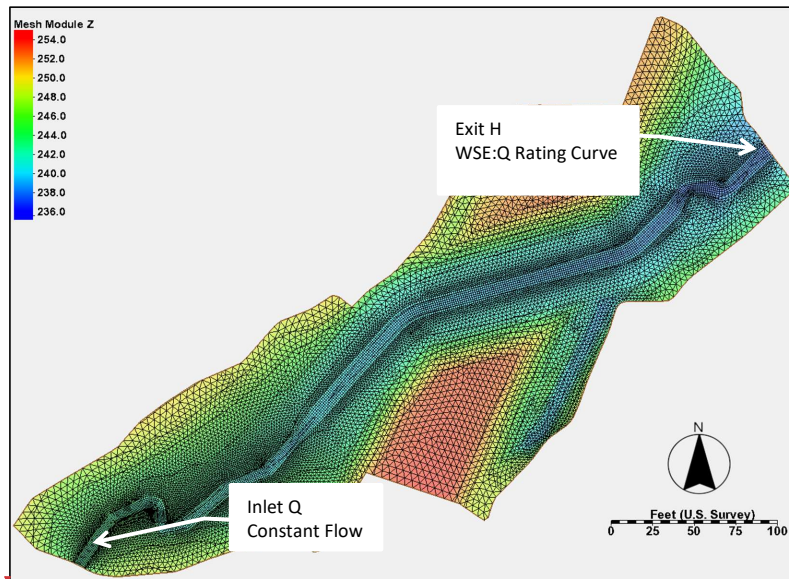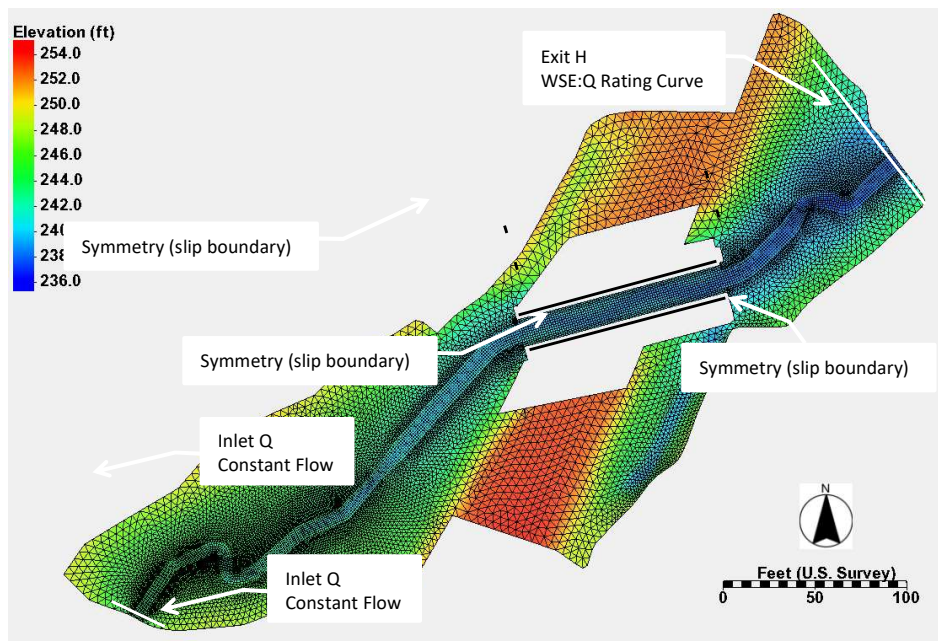Figure 34: Location of boundary conditions for the natural-conditions model

Figure 35: Location of boundary conditions for the proposed-conditions model

Figure 36: HY-8 culvert parameters for the existing conditions

4.1.5 *Model Run Controls*

The same model run control settings were used for each simulation performed. The end time was adjusted during model development so that the duration was long enough to achieve steady-state conditions. The model run controls are shown in Figure 37 with the simulation description and case name modified to be specific to each simulation.

4.1.6 *Model Assumptions and Limitations*

The SRH-2D hydraulic model was developed to determine the minimum hydraulic structure opening, establish the proposed structure low chord elevation (and associated freeboard), and characterize hydraulic parameters used to design the crossing structure, streambed, and LWM. There are several attributes of the data relied upon to develop the model that affect the resolution to which model output should be relied on. In particular, the survey data collected for developing the model terrain geometry were sufficient to capture macroscale variation in channel form and floodplain topography on the order of average channel width/depth/location and floodplain gradients. The spatial scatter of the survey point data was too coarse, however, to develop a model terrain capable of discerning an accurate and precise resolution of velocity distributions at smaller microtopographic scales, precluding predicting rapid spatial variation in hydraulic properties in association with bedform and instream roughness and flow obstruction variation. Accordingly, the designs are based on general, spatially averaged model predictions of velocity and shear stress, with an appropriate safety factor. Small scale variations in hydraulic properties should not be interpreted as signifying a meaningful feature of the design. Highly detailed design modeling of large wood structures is therefore not warranted, where structure stability and scour can be designed sufficiently using simply water depth and average channel values of velocity predicted by the model and increasing roughness locally.
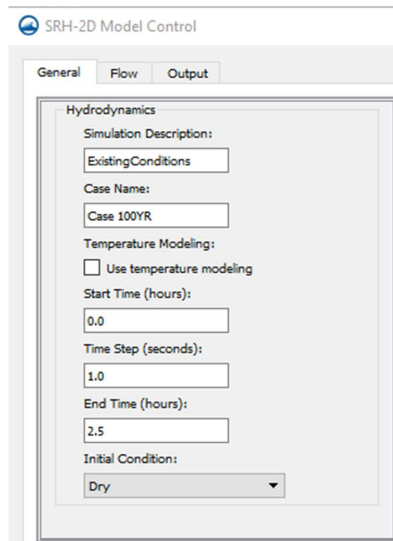
Figure 37: Model run controls

In addition, the topographic extent of the area surveyed did not extend beyond the model predictions of inundation extent for the most extreme flood events, where the flooding extended onto a small area of the adjoining surface generated from the LiDAR data. As seen in Figure 24, the LiDAR data appear to be biased high along the stream channel. This results in artificially concentrating flood flows onto the area within the bounds of the survey, and thus potentially over-predicting water surface elevations. However, the affected area is relatively small and located away from the crossing, thus should not materially affect the results.

The use of a steady peak inflow rate is an appropriate assumption to meet design objectives at this site. Using a steady peak inflow rate provides a conservative estimate of inundation extents and water surface elevation (WSEL) associated with a given peak flow, which is used to determine the structure size and low chord, and loose LWM stability. Similarly, the model predictions of peak velocity and shear stress are used to design general channel morphology, streambed composition, and both loose and fixed LWM stability. Each scenario is run for a sufficient time to fill storage areas and for WSELs to stabilize until flow upstream equals flow downstream. This modeling method does not account for the attenuation of peak flows between the actual upstream and downstream hydrographs, in particular with a large amount of storage upstream of the existing undersized culvert. During an actual runoff event, it is unlikely that the area upstream of the culvert would fill up entirely. An unsteady simulation could be used to route a hydrograph through the model to estimate peak flow attenuation for existing and proposed conditions. During an unsteady simulation, the areas upstream of the existing culvert would act as storage and, as a result, the flow downstream of the crossing would likely be less than the current design peak flow event. Estimates of the downstream increases to WSEL and flow based on the constant inflow model results may then underestimate the downstream flood impacts in the existing conditions simulations. This is expected to be less of an issue for the natural conditions and proposed PHD

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scenarios at this site, however, where the channel size is small relative to the hydraulic opening, and the channel slope too steep, for flow attenuation effects to be significant.

The SRH-2D model outputs an estimate of shear stress that is calculated using a 2-D vector adaptation of the 1-D uniform flow approximation based on depth and energy slope. The program substitutes Manning's equation to calculate the slope, which results in shear stress estimate being proportional to the square of the Manning's n coefficient. Because Manning's n is used in the modeling as a surrogate for various energy losses n addition to grain friction, the resulting estimates of shear stress cannot be used to size streambed substrates or evaluate local scour depth. Values are presented in this report for general reference, but should be treated generally as substantial over-estimates of the actual boundary shear stress (e.g., Pasternack et al. 2006). This is addressed directly in Section 5.1.

The model results and recommendations in this report are based on the conditions of the project site and the associated watershed at the time of this design. Any modifications to the site, man-made or natural, could alter the analysis, findings, and recommendations contained herein and could invalidate the analysis, findings, and recommendations. Site conditions, completion of upstream or downstream projects, upstream or downstream land use changes, climate changes, vegetation changes, maintenance practice changes, or other factors may change over time. Additional analysis or updates may be required in the future as a result of these changes.

4.2 Existing – Conditions Model Results

Hydraulic results were summarized and compared at specific locations for the existing-conditions. Four cross sections are located upstream of the crossing and three are located downstream of the crossing to provide a representation of the geometry and hydraulic characteristics of the site (Figure 38). The results of the existing-conditions hydraulic model are summarized for the main channel of each upstream and downstream cross section in Table 7, following the stationing depicted in Figure 39. Table 8 summarizes the average velocity within the left-overbank, right-overbank, and channel for each cross section. Results of the hydraulic model are presented along the longitudinal profile in Figure 40. Under the existing conditions, the culvert causes backwater upstream for the range of flows simulated. Pressure flow conditions occur for flood events larger than the 2-year event. The existing roadway does not overtop during the 500-year flood event. More detailed hydraulic model results are included in Appendix C.

During the 2-year flood event, the upstream and downstream cross sections have similar velocity, depth, and shear stress. At larger flood events, the culvert causes a substantial backwater influence. Further, the existing culvert is not aligned with the natural alignment of the watershed and the stream is channelized for approximately 140 feet. For flood events larger than the 2-year flood event, depths are greater at the upstream cross section than the downstream. Velocities and shear stress are lower at the upstream cross sections than the downstream. Figure 41 shows a typical upstream cross section. Velocity distributions for the 100-year flood event are shown in Figure 42.

At the upstream cross sections, average velocities for the main channel range from 0.3 foot per second (ft/s) for the 500-year event to 1.8 ft/s for the 2-year event. Downstream velocities range from 1.1 ft/s for the 2-year event to 3.1 ft/s for the 500-year event. Average shear stress values at the upstream cross

sections range from 0.0 pound per square foot (lb/SF) for the 500-year event to 0.6 lb/SF for the 2-year event. Average shear stress values at the downstream cross sections range from 0.2 lb/SF for the 2-year event to 1.6 lb/SF for the 500-year event. Depths at the upstream cross sections range from 1.1 foot at the 2-year event to 7.0 feet at the 500-year event. Depths at the downstream cross sections range from 1.3 foot for the 2-year event to 3.0 feet for the 500-year event.
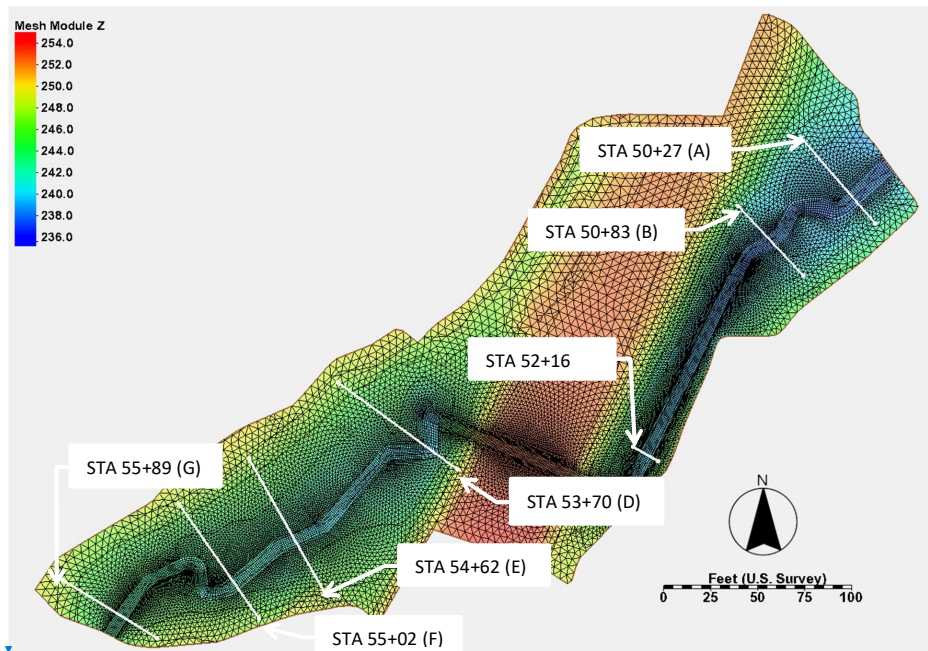
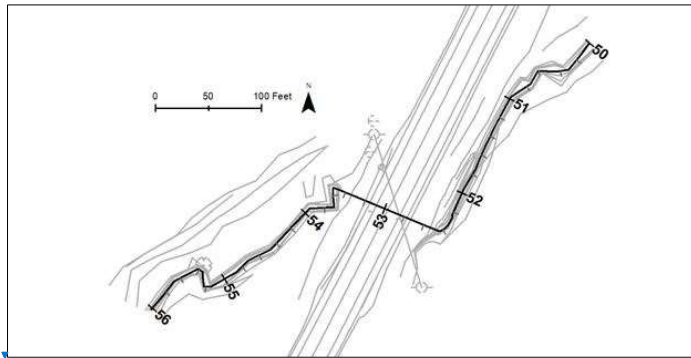**Figure 38: Locations of cross sections used for reporting existing-conditions hydraulic model results**

Figure 39: Longitudinal profile stationing for existing conditions

Table 7: Average main channel hydraulic results for existing conditions

Hydraulic parameter	Cross section (STA, name)	2-year	100-year	500-year
Average water surface elevation (ft)	50+27 (A)	239.5	240.0	240.2
	50+83 (B)	239.9	240.5	240.6
	52+16 (C)	241.5	242.6	242.9
	53+70 (D)	242.4	245.6	247.1
	54+62 (E)	242.7	245.6	247.1
	55+02 (F)	243.3	245.6	247.1
	55+89 (G)	244.8	245.8	247.1
Average water depth (ft)	50+27 (A)	1.2	1.8	1.9
	50+83 (B)	1.6	2.2	2.4
	52+16 (C)	1.4	2.5	2.8
	53+70 (D)	2.3	5.5	6.9
	54+62 (E)	1.1	3.9	5.4
	55+02 (F)	1.2	3.4	4.9
	55+89 (G)	1.5	2.5	3.8
Average velocity magnitude (ft/s)	50+27 (A)	1.8	2.3	2.4
	50+83 (B)	1.2	2.1	2.3
	52+16 (C)	2.0	3.0	3.3
	53+70 (D)	1.0	0.4	0.4
	54+62 (E)	1.5	0.6	0.4
	55+02 (F)	1.6	0.6	0.3
	55+89 (G)	1.2	1.6	1.0
Average shear stress (lb/SF)	50+27 (A)	0.6	0.8	0.9
	50+83 (B)	0.2	0.6	0.8
	52+16 (C)	0.7	1.3	1.5
	53+70 (D)	0.2	0.0	0.0
	54+62 (E)	0.5	0.1	0.0
	55+02 (F)	0.5	0.0	0.0
	55+89 (G)	0.3	0.5	0.2

Table 8: Existing-conditions average channel and floodplain velocities

Cross-section location	Q100 average peaks scenario (ft/s)		
	LOB[a]	Main ch.	ROB[a]
DS STA 50+27 (A)	1.2	2.3	1.1
DS STA 50+83 (B)	0.9	2.1	0.6
DS STA 52+16 (C)	1.2	3.0	1.0
DS STA 53+70 (D)	0.4	0.4	0.1
DS STA 54+62 (E)	0.3	0.6	0.4
DS STA 55+02 (F)	0.6	0.6	0.3
DS STA 55+89 (G)	0.5	1.6	0.6

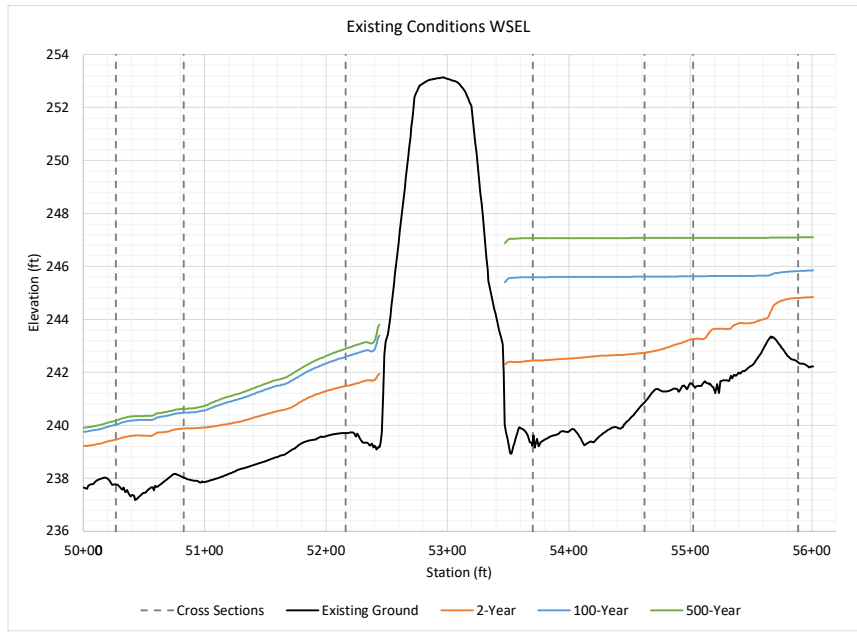Right overbank (ROB)/left overbank (LOB) locations were approximated based on the survey profiles.

Figure 40: Existing-conditions water surface profiles

Figure 41: Typical upstream existing channel cross section
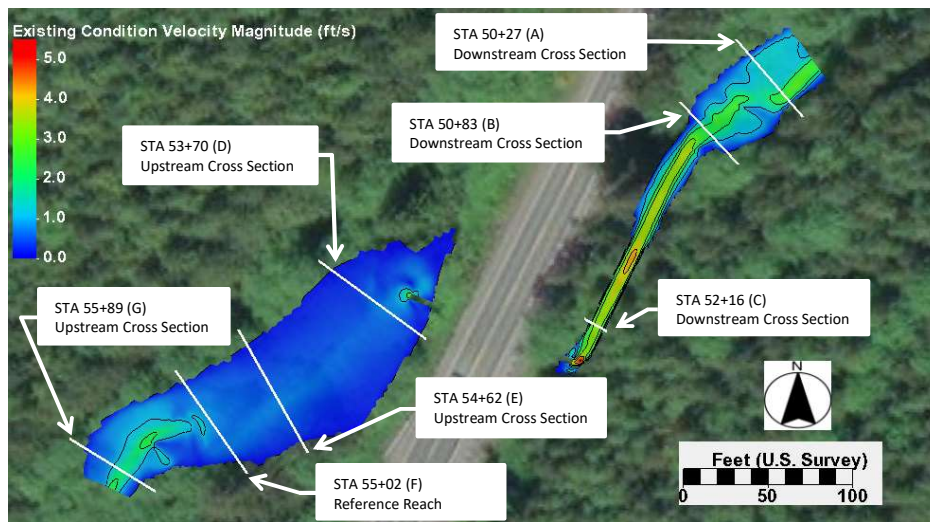
Figure 42: Existing-conditions 100-year velocity map with cross-section locations

4.3   Natural – Conditions Model Results

The existing culvert is skewed to the natural flow path of the watershed and its construction resulted in creating an unnatural, channelized reach downstream of the crossing. For the hydraulic model of the natural and proposed-conditions hydraulic opening, the stream was realigned to approximately follow the historical alignment prior to development (see Section 4.4.3). For the natural-conditions model, the roadway embankment was removed to provide a floodplain at the location of the existing crossing.

Locations of the cross sections used to report results for the natural-conditions hydraulic model are shown in Figure 43. The results of the natural-conditions hydraulic model are summarized for the main channel of each cross section in Table 9, following the stationing presented in Figure 44. Table 10 summarizes the average velocity within the left-overbank, right-overbank, and channel for each cross section. With the exception of STA 3+92, the hydraulic results were similar to one another. A natural constriction in the topography at STA 3+92 results in a narrower channel and a natural drawdown that causes flow to accelerate. In general, hydraulic results within the crossing are similar to upstream and downstream cross sections, which indicates that the natural-conditions model appears to be a reasonable surrogate for historical conditions. Results of the hydraulic model are presented along the longitudinal profile for the natural conditions in Figure 45. Figure 46 depicts the cross-section profile and predicted flood WSELs at the cross-section just upstream of the crossing. Velocity distributions are shown for the 100-year flood event in Figure 47. More detailed hydraulic model results are included in Appendix C.

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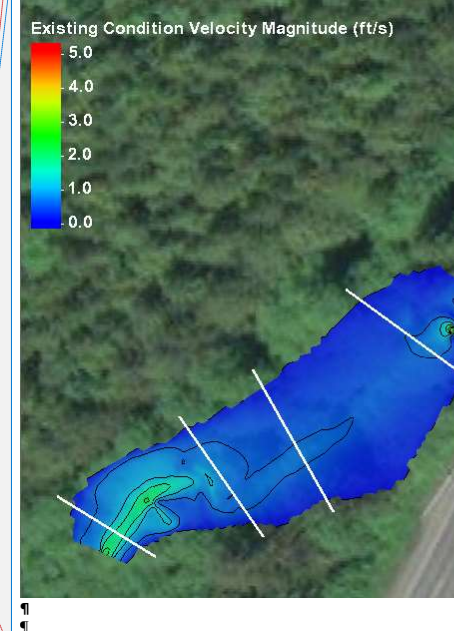
Deleted: Figure 42: Existing-conditions 100-year velocity map with cross-section locations¶

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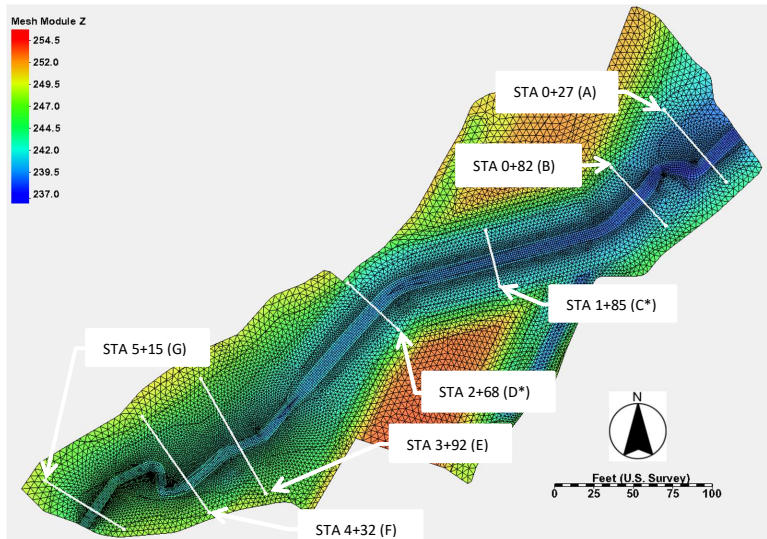
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Figure 43: Locations of cross sections used for reporting results of natural conditions model
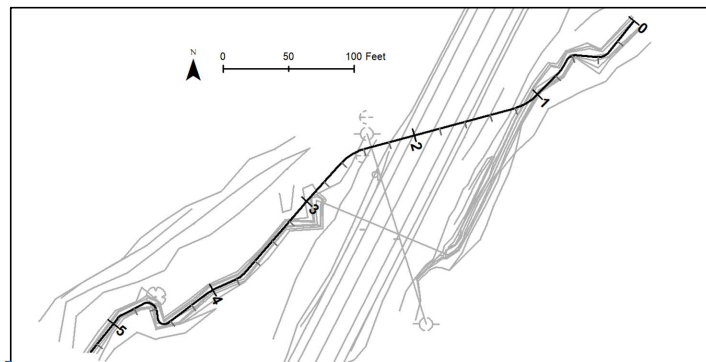
Figure 44: Longitudinal profile stationing for natural- and proposed-conditions models

Table 9: Average hydraulic results for natural condition

Hydraulic parameter	Cross section (STA, name)	2-year	100-year	500-year	2080 100-year
Average water surface elevation (ft)	0+27 (A)	239.5	240.0	240.2	240.1
	0+82 (B)	239.9	240.5	240.7	240.7
	1+85 (C*)	240.6	241.4	241.6	241.5
	2+68 (D*)	241.3	242.0	242.2	242.2
	3+92 (E)	242.4	243.3	243.5	243.5
	4+32 (F)	243.2	243.9	244.1	244.1
	5+15 (G)	244.8	245.5	245.7	245.6
Average water depth (ft)	0+27 (A)	1.2	1.8	1.9	1.9
	0+82 (B)	1.3	2.0	2.1	2.1
	1+85 (C*)	1.1	1.9	2.1	2.1
	2+68 (D*)	1.2	2.0	2.2	2.1
	3+92 (E)	1.3	2.2	2.4	2.3
	4+32 (F)	1.4	2.1	2.3	2.2
	5+15 (G)	1.0	1.8	1.9	1.9
Average velocity magnitude (ft/s)	0+27 (A)	1.8	2.3	2.4	2.3
	0+82 (B)	1.6	2.5	2.7	2.6
	1+85 (C*)	1.7	2.4	2.5	2.5
	2+68 (D*)	1.8	2.5	2.6	2.6
	3+92 (E)	2.7	3.0	3.1	3.1
	4+32 (F)	1.8	2.3	2.3	2.3
	5+15 (G)	0.8	1.4	1.6	1.6
Average shear stress (lb/SF)	0+27 (A)	0.6	0.8	0.8	0.8
	0+82 (B)	0.5	0.9	1.0	1.0
	1+85 (C*)	0.5	0.8	0.9	0.9
	2+68 (D*)	0.6	0.9	1.0	1.0
	3+92 (E)	1.3	1.3	1.3	1.3
	4+32 (F)	0.6	0.7	0.7	0.7
	5+15 (G)	0.2	0.5	0.6	0.6

Table 10: Natural-conditions velocities including floodplains at select cross sections

Cross-section location	Q100 average peaks scenario (ft/s)		
	LOB[a]	Main ch.	ROB[a]
DS STA 0+27 (A)	1.2	2.3	1.1
DS STA 0+82 (B)	0.8	2.5	0.8
DS STA 1+85 (C*)	0.9	2.4	0.9
US STA 2+68 (D*)	0.8	2.5	0.8
US STA 3+92 (E)	1.3	3.0	1.1
US STA 4+32 (F)	1.3	2.3	1.3
US STA 5+15 (G)	0.4	1.4	0.8

Right overbank (ROB)/left overbank (LOB) locations were approximated based on the survey profiles.

Figure 45: Natural-conditions water surface profiles

Figure 46: Natural-conditions STA2+68 (D*)

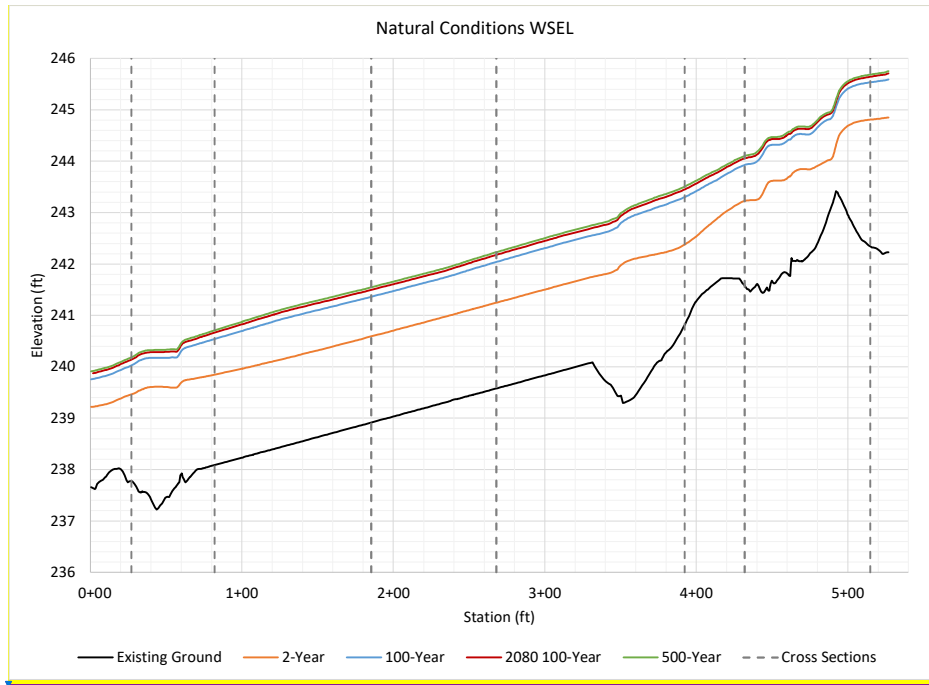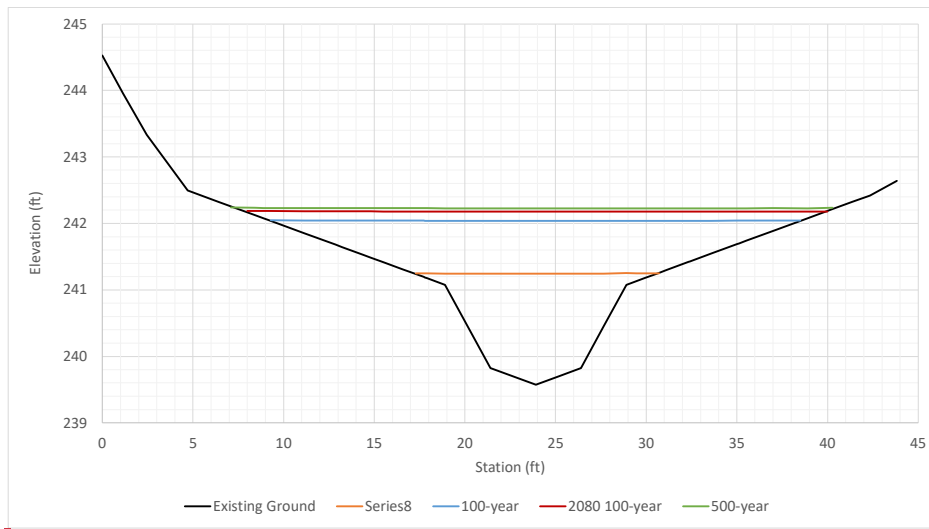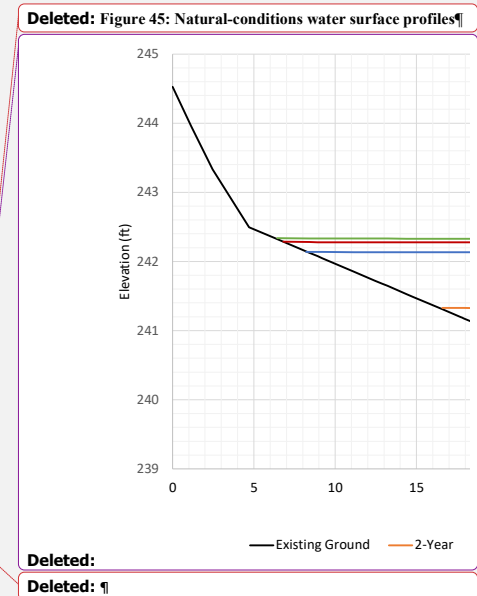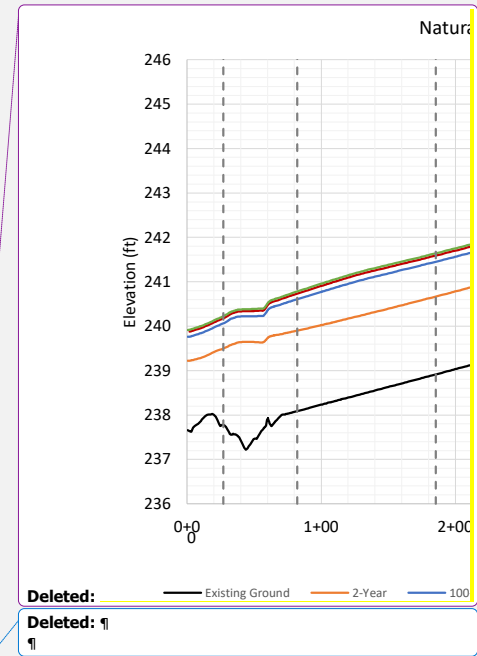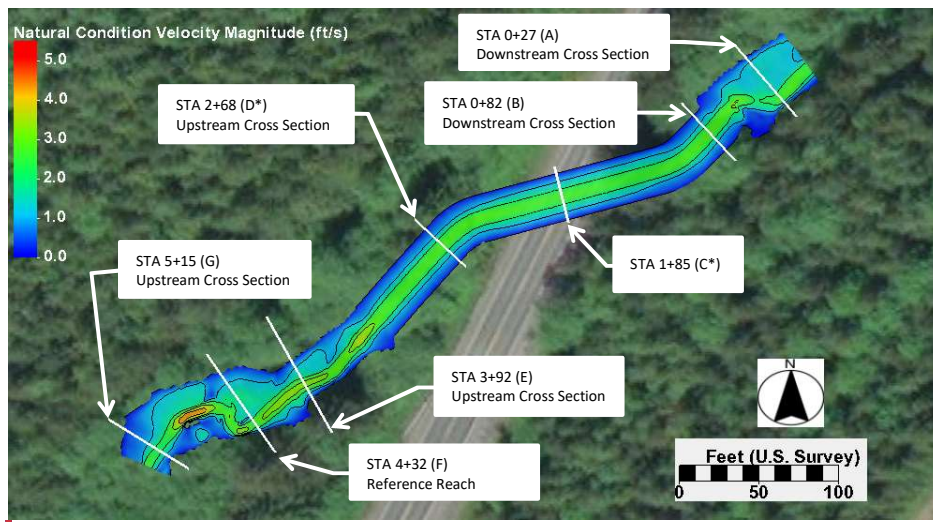**Figure 47: Natural-conditions 100-year velocity map with cross-section locations**
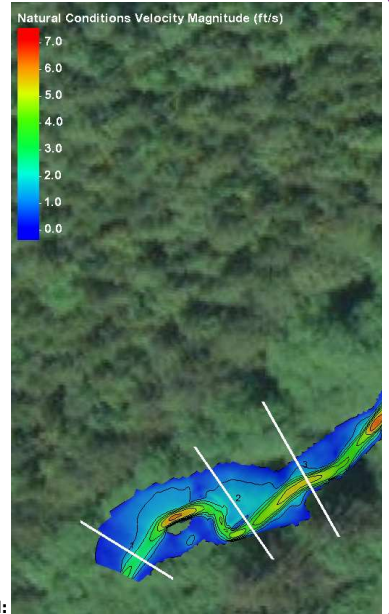
4.4 Proposed Channel Design

This section describes the development of the proposed channel cross-section and layout design.

4.4.1 Floodplain Utilization Ratio

The floodplain utilization ratio (FUR) is defined as the flood-prone width (FPW) divided by the BFW. A ratio under 3.0 is considered a confined channel and above 3.0 is considered an unconfined channel. The FPW was determined from the existing-conditions model results for the 100-year flood event. The FPW was calculated at five cross sections not under backwater influence of the existing culvert. At each cross section, the FPW was divided by the design BFW of 8.0 feet to calculate the FUR (Table 11). The average FUR is 4.4, which results in classifying the channel as 'unconfined'.

Table 11: FUR determination

Station	FPW (ft)	FUR
50+27 (A)	36.5	4.6
50+83 (B)	29.3	3.7
54+62 (E)	31.2	3.9
55+02 (F)	45.0	5.6
55+89 (G)	32.9	4.1
	Average	4.4

4.4.2 Channel Planform and Shape

The WCDG prefers in a stream simulation design that the channel planform and cross-section shape mimic conditions within a reference reach (Barnard et al. 2013). The proposed channel cross-section profile accordingly emulates WSDOT's typical reference channel-based design (Figure 48), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. A meandering planform is proposed within the replacement structure to increase total roughness within the culvert and accordingly reduce velocities, and to provide greater habitat complexity.

The bottom cross-section profile of the reference-based channel has a bottom side slope of 10 horizontal (H):1 vertical (V) between the thalweg and bank toes, 2H:1V streambank slopes, and an overbank terrace at roughly a 10H:1V slope to create a channel similar to the observed existing channel shape. The existing-conditions model results show that the 2-year flood event goes overbank in the existing channel. It is expected that the bottom profile will continue to adjust naturally during high water, where the proposed profile provides a reasonable starting point for subsequent channel profile evolution and bank stability will be provided via bioengineering design. Overall, the proposed design cross-section profile approximates reference reach conditions (Figure 49).
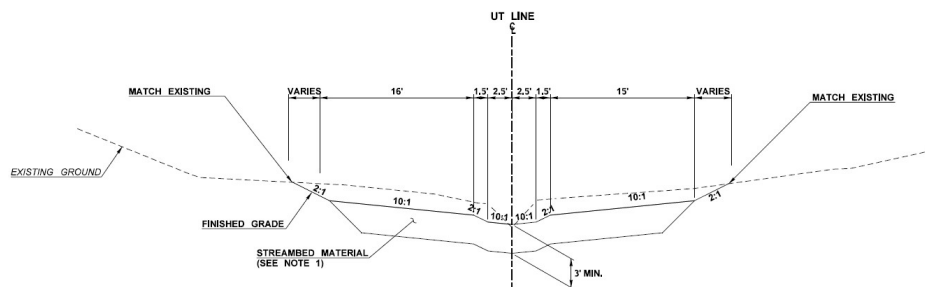
Figure 48: Reference channel-based design cross section for outside the culvert footprint.
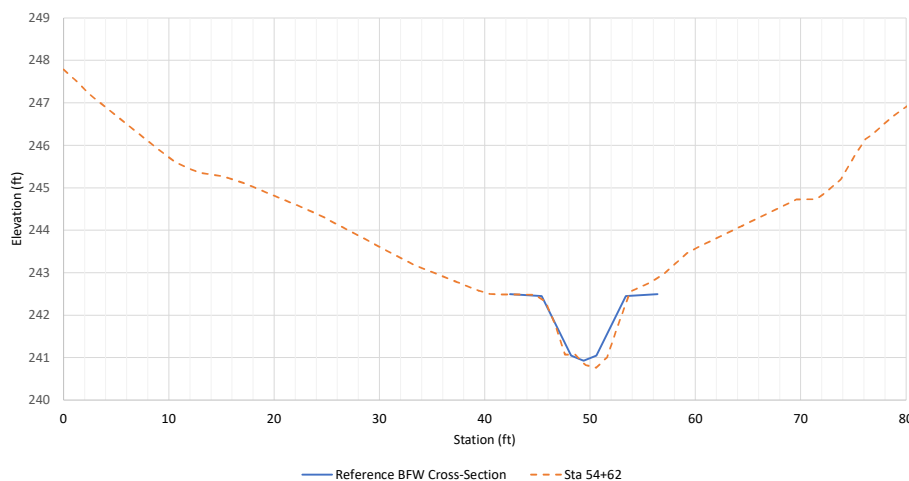

Figure 49: Comparison of design cross-section with a representative cross-section outside of the replacement structure footprint

Bioengineering methods can be implemented towards long term stability of the channel cross-section profile and planform outside the culvert. This does not necessarily apply to under replacement structures that are not long, high bridges, however, as is the case for this site where bank stabilizing vegetation typically will not grow and use of large woody material presents special constructability and maintenance problems. Except for very slow, low gradient channels, it is not possible to preserve a steep side slope without vegetation or specifying a particle size that is markedly larger than that typically specified for an alluvial, mobile streambed and is stable under all flows. For the project stream's gradient, side slope stability equations predict that gravel and cobble substrates will mobilize readily unless the cross-section is relatively flat (see Appendix D). Indeed, this is a primary reason why the profiles of constructed stream simulation designs using gravel and cobble tend to wash out and flatten within the first winter season of high flows. In the case of the project stream, shear stress calculations based on the hydraulic model predictions of velocity during the 100-year flood peak indicate that even a

Deleted: It is reasonable to use that as the basis for designing a channel outside of the replacement structure because bioengineering methods can be implemented towards long term stability of the channel cross-section profile and planform. This is not necessarily the case for under replacement structures that are not long, high bridges, however, where bank stabilizing vegetation typically will not grow and use of large woody material presents special constructability and maintenance problems. Except for very slow, low gradient channels, it is not possible to preserve a steep side slope within a smaller replacement structure such as that proposed for this site without vegetation, or without specifying a particle size that is markedly larger than that typically specified for an alluvial, mobile streambed and is stable under all flows. For the project stream's gradient, side slope stability equations predict that gravel and cobble substrates will mobilize readily unless the cross-section is relatively flat (see Appendix D). Indeed, this is a primary reason why the profiles of constructed stream simulation designs using gravel and cobble tend to wash out and flatten within the first winter season of high flows. In the case of the project stream, calculations based on the hydraulic model predictions of shear stress and velocity during the 100 year flood peak indicate that even a flat bottom cross-section is not stable when the streambed grain size distribution approximates the sieve sample in Table 3 (Appendix D). Consequently, the cross-section profile design within the replacement structure needs to be based more on hydraulic design than on emulating a reference reach morphology. ¶
Outside of the replacement structure, the proposed channel cross-section profile generally follows WSDOT's typical reference channel-based design (Figure 48), with the relative location of the thalweg across the section varying depending on whether the channel is straight or curving. The existing-conditions model results show that the 2-year flood event goes overbank in the existing channel conveys with overbank minimal expansion into the overbanks. The proposed channel shape consists of 10 horizontal (H):1 vertical (V) slopes between the toes and 2H:1V bank slopes fit within the design bankfull width, and floodplain benches with 10H:1V slopes. The proposed design cross-section profile overall approximates the reference reach morphology (Figure 49).¶
As discussed above, however, the proposed design cross section within the structure will reflect the constraint posed by side slope stability of an unarmored, non-cohesive streambed, and the geomorphic observation that gravel supply rates to the culv... [10]

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Deleted: Figure 48: Reference channel-based design cross section for outside the culvert footprint.¶
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Deleted: Figure 49: Comparison of design cross-section with a representative cross-section outside of the replacement structure footprint ¶

Deleted: An alternative profile and sufficiently stable substrates to preserve the profile was consequently considered for the design of the streambed within the replacement culvert. A V-shaped cross-section provides a balance between concentrating low flows into a passage lane via a steep side slope, and ensuring more of the streambed material placed in the culvert remains within the culvert during flooding via a gentler side slope. It also can reduce the potential for debris blockage to form. The cross-section profile design problem then becomes deciding on an appropriate s... [11]

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flat bottom cross-section is not stable when the streambed grain size distribution approximates the reference reach pebble count in Table 3 (see Section 5).

However, the stream simulation design methodology as stipulated in WAC 220-660-190 is based on emulating a mobile bed reference channel morphology and substrate within the structure as well as outside, irrespective of future evolution of the channel cross-section profile. Given that vegetative stabilization is not feasible for this site, and measures to fix the bed in place are inconsistent with the stream simulation design approach, an alternate method is needed to counter flattening of the bed and preserve a meander morphology. Accordingly, the proposed design consists of a cobble surface armor layer placed on top of each meander bar. The cobble is sized to become partially mobile around the 100-year flood level so that material can adjust as needed yet remain within the culvert with the goal of preserving a meandering planform. The design rationale for specifying the grain size distribution of the cobble armor layer is described in greater detail Section 5. In general, the following considerations influenced design of the meander bars:

- The meander bars should be composed of a surface layer consisting of coarser cobble material that can self-organize into a stable, natural arrangement under a 100-year flood flow to avoid flattening out of the cross-section profile. Specific criteria include:
  - The grain size distribution of the material should reflect a critical dimensionless shear stress between 0.03 and 0.06, and closer to 0.03 in order to maintain a riffle form (e.g., Pasternack and Brown 2013; see Section 5.1).
  - The thickness of the surface layer should be at least twice the D_{90} of the cobble material, which is the general expected disturbance depth of a coarse bedded surface layer that is disturbed by mobilizing flows (cf. Wilcock et al. 1996; DeVries 2002). It is not necessary to extend this material all the way down to the bottom of the streambed fill because it is designed to adjust with streambed regrading but generally remain at the same location within the culvert. However, in cases where an additional safety factor is desired, the layer can extend down to the depth of the constructed thalweg.
- The design goal for spacing of the bars should reflect a maximum head drop over a naturally formed riffle, rather than emulating a classic geomorphic pool-riffle spacing criterion, given the meander bars are intended to be effectively stable. To reduce the potential for re-grading to adversely affect upstream swimming ability, the head drop between bar centerlines (across the channel) should be below typical criteria for juvenile salmonids to accommodate upstream movements of other native fish species. For this site, a head drop of 3 inches between bar apices was selected based on professional judgment, where the drop is expected to be across a naturally formed riffle after the streambed is reworked by floods, assuming worst case regrading occurs such that the gradient of the streambed between bar apices becomes flatter.
- The bar material should not protrude above the design surface, where the intervening material is designed to be in flush with the edge of the bar material and is sized to be stable on the prevailing stream gradient and side slope.
- Additionally, stable habitat boulders (typically 2-man or larger; WSDOT specification 9-03.11(4)) can be placed embedded into the streambed surface to increase channel roughness, which helps slow velocities within the structure and provide hydraulic sheltering for fish during high flows.

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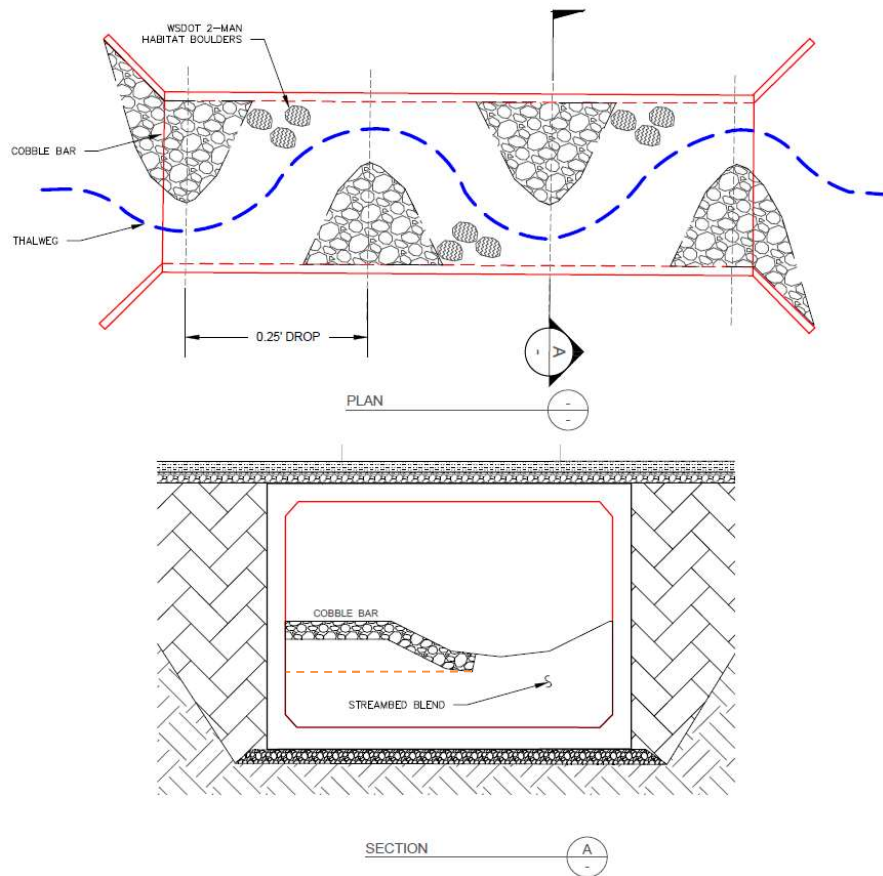The corresponding proposed design is depicted schematically in Figure 50.

Figure 50: Schematic of proposed channel planform (top) and cross-section (bottom) layout inside the culvert. If there is concern of future loss of bar material to downstream, the thickness of the cobble layer can be increased to the dashed line.

4.4.3 *Channel Alignment*

As indicated above, the existing culvert was realigned from the flow path of the historical channel, with an excavated channel reconnecting it with the natural flow path. To restore the stream to a state more representative of the historical channel and alignment, the proposed channel alignment involves returning the flow path to its approximate historic footprint. The proposed channel grading begins approximately 70 feet upstream of the existing culvert inlet and ends approximately 180 feet downstream of the existing culvert outlet. The total length of the proposed channel grading is approximately 290 feet. While the approximately 140 feet length of stream channel between the outlets

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of the existing and proposed culverts is lost, this section is channelized and lacking habitat complexity in general. Instead, roughly 60 feet of new channel will be created on the upstream side with substantially greater habitat complexity, and by realigning the stream channel back to its old course, geomorphic equilibrium will be restored between upstream and downstream stream grades (see Section 2.8.4).

4.4.4   *Channel Gradient*

The WCDG recommends that the proposed culvert bed gradient not be more than 25 percent steeper than the existing stream gradient upstream of the crossing (WCDG Equation 3.1). Realigning the culvert to the historic footprint will result in a locally lower grade than upstream and downstream, where the proposed channel gradient is 0.8 percent and the average upstream and downstream channel gradients are approximately 1.1 percent, resulting in a slope ratio of 0.7 which satisfies WCDG recommendations. Despite the local slope reduction, realigning the replacement structure to be approximately in line with the historic channel planform location will result in a design streambed that will still be approximately in line with upstream and downstream grades as shown in section 2.8.4. In addition, the lower slope within the culvert is associated with a low risk of degradation locally, and the slope is sufficiently steep to competently transport the characteristic sediment load such that there is also negligible risk of aggradation.

4.5   Design Methodology

The proposed culvert hydraulic design was developed using the 2013 *Water Crossing Design Guidelines* (Barnard et al. 2013) and the WSDOT *Hydraulics Manual* (WSDOT 2019). Based upon these two documents, the unconfined bridge design method was determined to be the most appropriate at this crossing because the FUR was calculated to be greater than 3.0. Although the BFW is less than 15 feet and the proposed channel gradient meets the slope ratio to meet stream simulation requirements, the unconfined bridge approach provides additional conveyance capacity in the overbanks to reduce main channel velocities during extreme flood events.

4.6   Future Conditions: Proposed 15-Foot Minimum Hydraulic Opening

The determination of the proposed minimum hydraulic opening width is described in section 4.7. A 15-feet wide opening was modeled as an open channel with 8 ft BFW channel and floodplain, with vertical side walls. The resulting hydraulic predictions were used in the analyses described in section 4.4 to yield conservative design parameters for freeboard and substrate sizing, and for guiding final design of a persistent cross-section profile within the culvert absent bank-stabilizing vegetation.

Locations of cross-sections used to report results for the proposed conditions hydraulic model are shown in Figure 51. The stationing for each cross section is assigned using the proposed alignment as shown in Figure 44.

STA 1+85 (C*)

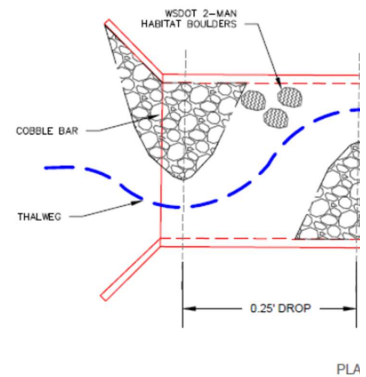STA 5+15 (G)

STA 2+68 (D*)

STA 3+92 (E)

Figure 51: Location of cross section used for results reporting

The results of the proposed-conditions hydraulic model are summarized for the main channel of each cross section in Table 12. Main channel and floodplain velocities are summarized in Table 13. The hydraulic results within the proposed structure (STA 1+85) are very similar to the hydraulic results at the cross section upstream of the structure (STA 2+68). Under the proposed conditions, the culvert no longer causes backwater upstream for the range of flows simulated as shown in Figure 52. The roadway does not overtop for flood events equal to or less than the magnitude of t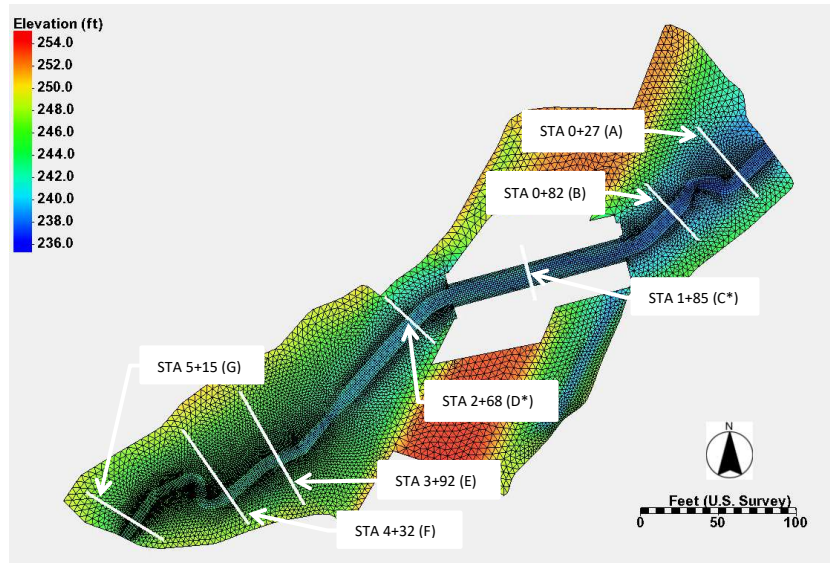he 500-year flood event. Figure 53 shows a typical cross section through the proposed structure. Velocity distributions for the 100-year flood event are shown in Figure 54. Table 13 summarizes the average velocity within the left-overbank, right-overbank, and channel for the 100-year flood event at each cross section. Velocity distributions for the 2080 predicted 100-year flood event are shown in Figure 55.

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Deleted: Figure 51: Location of cross section used for results reporting¶

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Moved up [4]: The hydraulic results within the proposed structure (STA 1+85) are very similar to the hydraulic results at the cross section upstream of the structure (STA 2+68

Deleted:). Depths within the structure range from 0.9 foot for the 2-year event to 1.71.8 feet for the 2080 100500-year event. Velocities range from 2.22.1 ft/s for the 2-year event to 3.53.6 ft/s for the 2080 100500-year event. Shear stress ranges from 0.20.3 lb/SF for the 2-year event to 0.40.5 lb/SF for the 2080 100-year event. Depths at the cross section upstream of the structure range from 1.10.9 foot for the 2-year event to 2.01.8 feet for the 2080 100500-year event. Velocities range from 1.9 ft/s for the 2-year event to 2.8 ft/s for the 2080 100-year event. Shear stress ranges from 0.8 lb/SF for the 2-year event to 1.4 lb/SF for the 2080 100-year event. ¶

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Table 12: Average main channel hydraulic results for proposed conditions

Hydraulic parameter	Cross section (STA, name)	2-year	100-year	500-year	2080 100-year
Average water surface elevation (ft)	0+27 (A)	239.5	240.0	240.2	240.1
	0+82 (B)	239.7	240.4	240.5	240.5
	1+85 (C*)[a]	240.1	240.8	241.0	240.9
	2+68 (D*)	241.0	241.7	241.9	241.8
	3+92 (E)	242.4	243.3	243.5	243.4
	4+32 (F)	243.2	243.9	244.1	244.1
	5+15 (G)	244.8	245.5	245.7	245.6
Average water depth (ft)	0+27 (A)	1.2	1.8	1.9	1.9
	0+82 (B)	1.4	2.0	2.1	2.1
	1+85 (C*)[a]	0.8	1.5	1.6	1.6
	2+68 (D*)	1.0	1.7	1.9	1.8
	3+92 (E)	1.3	2.2	2.4	2.3
	4+32 (F)	1.4	2.1	2.3	2.2
	5+15 (G)	1.0	1.7	1.9	1.9
Average velocity magnitude (ft/s)	0+27 (A)	1.8	2.3	2.4	2.4
	0+82 (B)	1.4	2.1	2.2	2.2
	1+85 (C*)[a]	2.3	3.3	3.5	3.5
	2+68 (D*)	1.9	2.6	2.8	2.7
	3+92 (E)	2.8	3.1	3.2	3.2
	4+32 (F)	1.8	2.3	2.3	2.3
	5+15 (G)	0.8	1.4	1.6	1.6
Average shear stress (lb/SF)	0+27 (A)	0.6	0.8	0.9	0.8
	0+82 (B)	0.3	0.6	0.7	0.7
	1+85 (C*)[a]	0.3	0.5	0.5	0.5
	2+68 (D*)	0.7	1.1	1.1	1.1
	3+92 (E)	1.3	1.3	1.4	1.4
	4+32 (F)	0.6	0.8	0.8	0.8
	5+15 (G)	0.2	0.5	0.6	0.5

[a] – Inside proposed structure

Table 13: Proposed velocities including floodplains at select cross sections

Cross-section location	Q100 average peaks scenario (ft/s)		
	LOB[a]	Main ch.	ROB[a]
DS STA 0+27 (A)	1.1	2.3	1.1
DS STA 0+82 (B)	0.7	2.1	0.9
DS STA 1+85 (C*)	1.6	3.3	3.2
US STA 2+68 (D*)	0.8	2.6	1.0
US STA 3+92 (E)	1.2	3.1	1.1
US STA 4+32 (F)	1.3	2.3	1.3
US STA 5+15 (G)	0.4	1.4	0.7

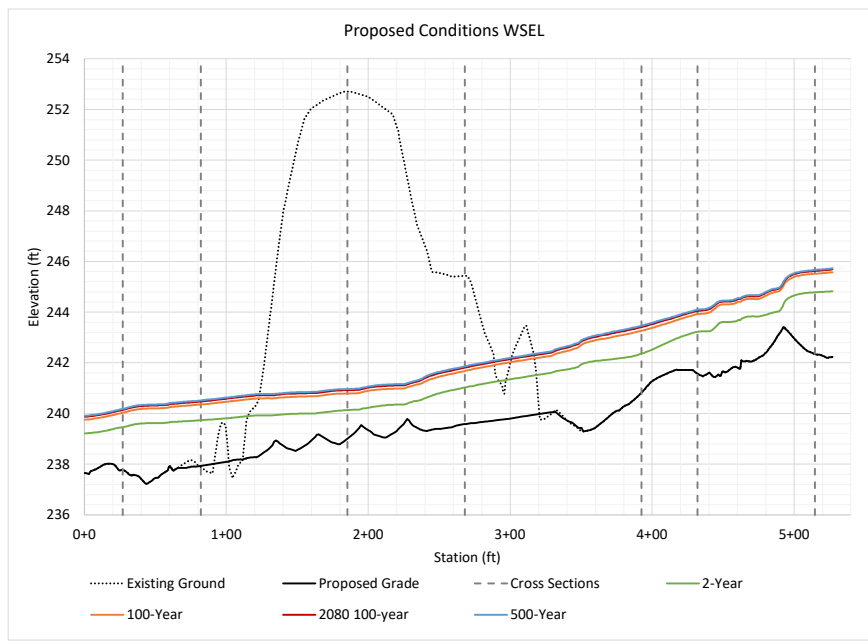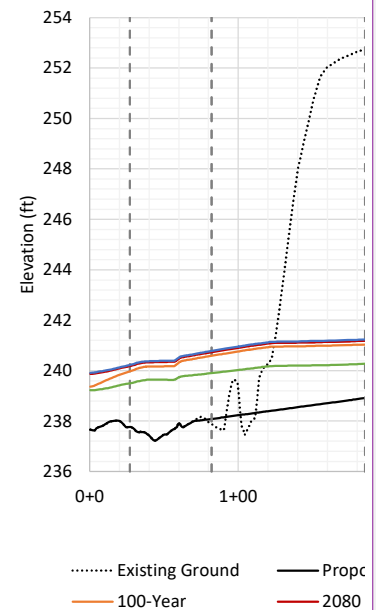Right overbank (ROB)/left overbank (LOB) locations were approximated based on the survey profiles.
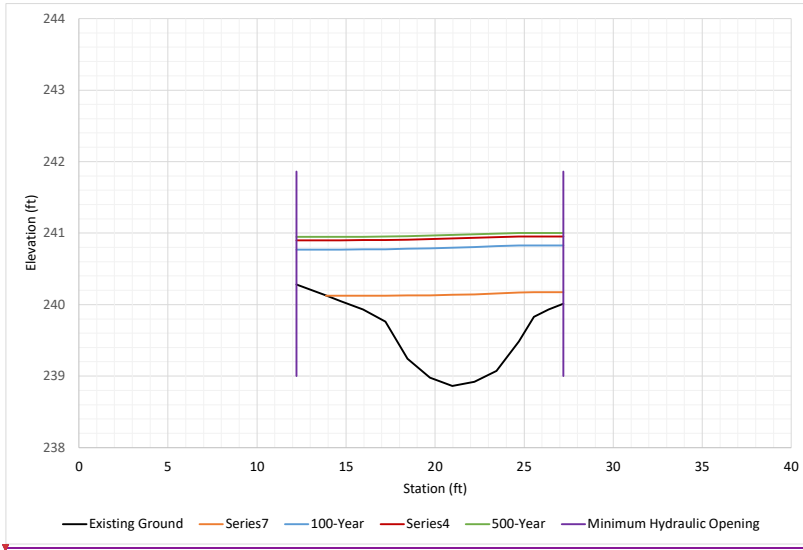

Figure 52: Proposed-conditions water surface profiles
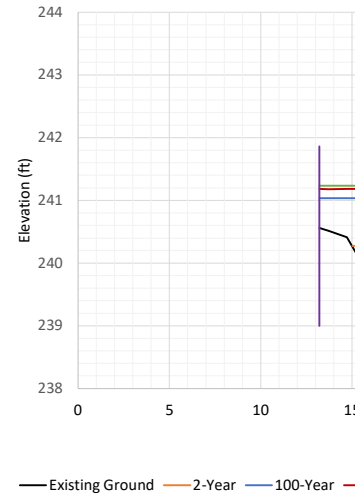
Figure 53: Typical section through proposed structure (STA 1+85)

Figure 54: Proposed-conditions 100-year velocity map
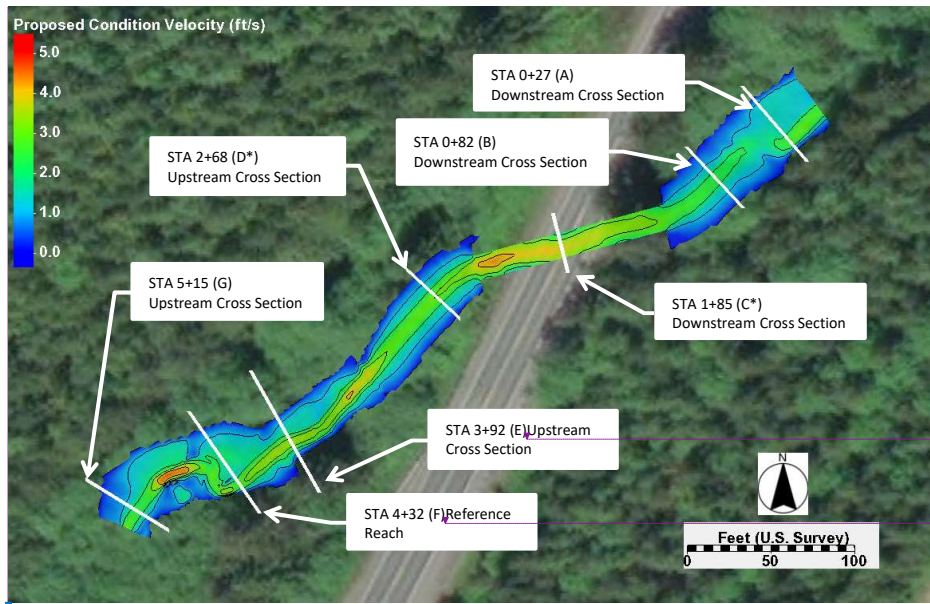
Figure 55: Proposed-conditions 2080 predicted 100-year velocity map

4.7 Water Crossing Design

Water crossing design parameters include structure type, minimum hydraulic opening width and length, and freeboard requirements.

4.7.1 Structure Type

A concrete box culvert is proposed for this site.

4.7.2 Minimum Hydraulic Opening Width and Length

The hydraulic opening is defined as the width perpendicular to the creek beneath the proposed structure that is necessary to convey the design flow and allow for natural geomorphic processes. The hydraulic opening width assumes vertical walls at the sides of the edge of the minimum hydraulic opening width unless otherwise specified. The starting point for the design of all WSDOT structures is Equation 3.2 of the WCDG, rounded up to the nearest whole foot. For this crossing, a minimum hydraulic opening of 12 feet was determined to be the minimum starting point based on the equation. Subsequent modeling indicated that a wider opening was needed to reduce velocities through the culvert to meet WSDOT's recommended velocity-based criterion for protecting against adverse fish passage conditions and increased channel instability. Specifically, the present day and projected 2080 100-year flood magnitudes were evaluated for the proposed and reference conditions to evaluate the criterion which is represented by a velocity ratio. The ratio was calculated as the mean channel average

velocity inside the structure divided by the analogous value in a reference reach, and provides a measure of the extent to which flow is accelerated inside the structure. Analysis indicated that a structure width of 13 feet would result in a velocity ratio equal to 1.1, for the 100-yr flow event, meeting WSDOT's criterion (WSDOT 2019). Simulations of alternative structure widths of 15 feet and 18 feet resulted in a similar magnitude ratio, where the water surface profiles through the structure were similar. Although a 13-feet wide structure is sufficient to meet the design criteria, it was agreed in December 2021 discussions between the QIN, WDFW, and WSDOT to increase the minimum hydraulic opening to 15 feet to provide additional low velocity zones along the structure sides at the 100-year event. The velocity ratios for this proposed structure are given in Table 14.

The proposed structure length is approximately 114 feet, which is within the WCDG's maximum length:width ratio criterion of 10 for a stream simulation design. The ultimate length will be confirmed at a later stage of design.

Table 14: Velocity ratio calculated for the Ptoposed 15 feet wide structure

Simulation	Reference 100-year velocity (ft/s)	Proposed 100-year velocity (ft/s) Culvert, STA 1+85	Velocity Ratio
Present Day 100-year	2.7	3.1	1.1
2080 100-year	2.8	3.2	1.1
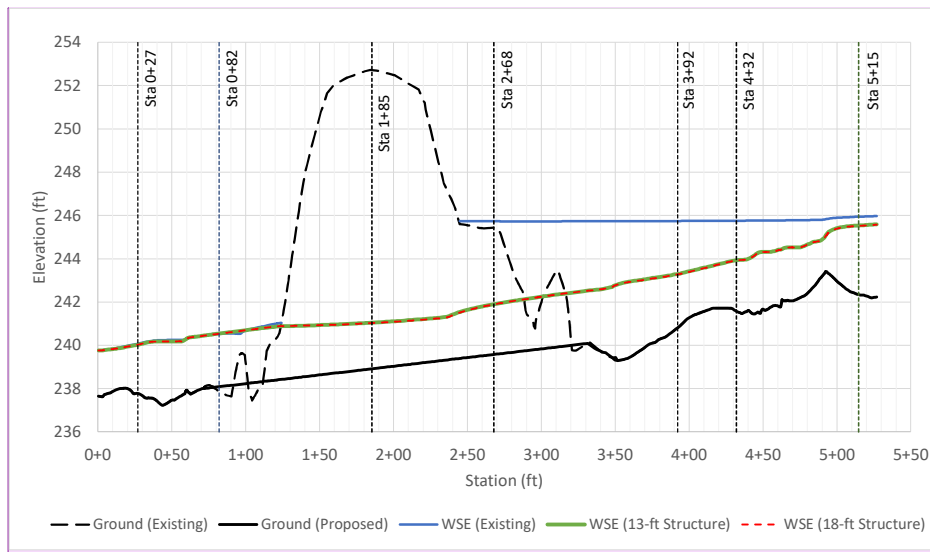
Figure 56: for 13 feet and 18 feet wide hydraulic opening widths

4.7.3 *Freeboard*

Freeboard is necessary to allow the free passage of debris expected to be encountered. The WCDG generally suggests a minimum 2-feet clearance above the 100-year WSEL for streams with a BFW of between 8-15 feet to adequately pass debris (Barnard et al. 2013). WSDOT also desires a minimum vertical clearance between the culvert soffit and the streambed thalweg for maintenance equal to 6 feet where possible. The culvert freeboard is designed to accommodate climate change through modeling of the 2080 100-year flood estimate. The hydraulic modeling indicates that the maintenance-based goal will exceed the clearance required to meet the 2 feet hydraulic-based criterion associated with the proposed design when constructed.

Long-term aggradation and degradation are expected to be negligible at this location (see section 2.8.4). Thus additional freeboard does not appear to be required at this site (Table 15).

Table 15: Parameters relevant to freeboard specification for proposed replacement structure

Parameter	2080 100-Year Coincident Flood Predictions	
	At Inlet	At Outlet
Thalweg elevation (ft)	239.4	238.5
Maximum WSEL (ft)	241.4	240.7
Minimum low chord elevation to provide 2 feet of freeboard (ft)	243.4	242.7
Minimum low chord elevation to provide 6 feet maintenance access (ft)	245.4	244.5
Recommended low chord elevation, with future aggradation (ft)	245.4	244.5

4.7.3.1 Past Maintenance Records
WSDOT Area 4 Maintenance has indicated that there is no record of LWM blockage and/or removal and/or sediment removal at this crossing. The only required maintenance has been limited to routine maintenance using a hand shovel.

4.7.3.2 Wood and Sediment Supply
The contributing basin is predominantly forested with a supply of approximately 20 year old trees growing in the riparian management zone after previous timber harvest, that may be a potential future source of LWM. However, as described in section 2, any tree that falls into the channel is expected to remain in place, and only wood pieces smaller than the design opening width can be expected to be transported to the replacement culvert inlet.

4.7.3.3 Flooding
As described in Section 2.3, the site is not located in a FEMA-delineated floodplain. There is no history of flood-related maintenance or overtopping, which is consistent with the hydraulic simulation results for the existing-conditions model that predict the roadway does not overtop at the 500-year flood event peak flow. There is a backwater influence of the existing structure that is predicted to extend at least 200 feet upstream for the 100-year flood event based on floodplain inundation extents. The proposed

hydraulic opening will increase the capacity of the crossing and significantly reduce the backwater in comparison to the existing conditions.

4.7.3.4 Future Corridor Plans

There are currently no long-term plans to improve U.S. 101 through this corridor.

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4.7.3.5   Impacts

It is not anticipated that the road grade will need to be raised to accommodate the proposed minimum hydraulic opening with the desired minimum clearance. A final decision will be made at a later design phase.

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4.7.3.6 Impacts to Fish Life and Habitat

In discussion with WDFW and the tribes, it is expected that the proposed minimum hydraulic opening of 13 feet will result in no substantial impacts to fish life and habitat.

5   Streambed Design

The streambed design considered the local characteristic grain size distribution (GSD) of gravel collected in pebble counts, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two grainsize distributions will be developed during the FHD phase, one for the streambed mix, and the second for a cobble armor surface on the proposed meander bars within the replacement structure. In addition, large wood material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.

5.1   Bed Material

Where neither of the other two alternative approaches identified in Section 1.0 are indicated for implementation, the injunction requires that the design follow the stream simulation methodology as described in the WAC and WCDG (Barnard et al. 2013). WAC 220-660-190 stipulates that "The median particle size of sediment placed inside the stream-simulation culvert must be approximately twenty percent of the median particle size found in a reference reach of the same stream. The department [WDFW] may approve exceptions if the proposed alternative sediment is appropriate for the circumstances." The reference reach of this stream is primarily composed of fines, with some isolated gravel patches. The proposed streambed gradation is more consistent with a pebble count of the isolated gravel as discussed in Section 2.8.3, as it is not practical to construct a culvert bed consisting completely of fines. However, WSDOT's streambed sediment specification, which has a larger D_{50}, represents the smallest constructible bed material for the project. Therefore, the proposed design is based on WSDOT's standard specifications for streambed sediment and cobble, as described below.

The evaluation of streambed instability risk focused on evaluating the stability of the D_{84} size at the 2- and 100-year flood peaks. WSDOT's standard worksheet for evaluating the stability of the D_{84} size using the modified Shields stress method (USFS 2008) is presented in Appendix D, based on assuming intermittent transport generally occurs when the dimensionless ("Shields") shear stress is less than 0.03 in value, which corresponds to the verge of mobility. Partial mobility falls with the range 0.03-0.06 (Lisle et al. 2000; Wilcock et al. 1996; Pasternack and Brown 2013). To emulate a partially adjustable streambed for this design, the critical dimensionless shear stress for the modified Shields stress method was set to 0.045, using estimates of shear stress.

The SRH-2D model outputs an estimate of shear stress, but the result is based on a 2-D vector adaptation of the uniform flow, wide channel 1-D approximation, and accordingly is a significant over-estimate compared with that derived from velocity profiles (Wilcock 1996; Pasternack et al. 2006; DeVries et al. 2014). Pasternack and Brown (2013) determined that the type of equation used more closely matches the velocity profile-derived estimate when the velocity is evaluated near the bed. However, SRH-2D calculates a mean column velocity, but that can be used to estimate near bed shear velocity and thus shear stress. Two different velocity relations based on the rough form of the law of the wall were evaluated accordingly, and they gave comparable order of magnitude predictions of shear stress (Richards 1982; Pasternack and Brown 2013). The larger of the two estimates was used to

evaluate the mobility of the D_{84} following the modified Shields stress method. The modified Shields approach documented in Appendix D predicts that the native gravel D_{84} size should be unstable at the 100 year flood, whereas a size around 1.3 inches should be stable.

The geomorphic reach conditions are such that the supply rate of native gravel from upstream would be insufficient to replace gravel mobilized from the culvert streambed over the long term. This is a significant constraint on the streambed design. Therefore, the proposed D_{84} exhibiting limited mobility up to the 100-year event is appropriate for this crossing, rather than the native material. In addition, the proposed meander bars are designed to remain stable at the 100-year event and the retain the proposed cross-sectional shape of the stream in the absence of vegetation growing within the culvert structure. For ensuring the general persistence of meander bars within the replacement structure and reducing the potential for flattening and regrading of the streambed profiles, the proposed meander bar gradation should be stable on a side slope that is intermediate to 2H:1V and a flat cross-section profile. A 7H:1V side slope was selected as a design goal because it concentrates low flows for fish passage, and allows for a constructible transition to the design bottom slope of the reference cross-section depicted in Figure 48. Equations for side slope stability at the 100-year flood peak were applied from Mooney et al. (2007). A D_{50} = 0.9 inches is estimated to be required for a stable 7H:1V side slope at the 100-year flood peak, with a D_{max} of approximately 5.4 inches following the WCDG. This D_{max} value is generally coarser than other guidelines for substrate stability (e.g., USACE 1994; Mooney et al. 2007), according to which a 4"-minus mix would likely also suffice. The proposed meander bar design gradation was therefore specified to consist of approximately 70% streambed sediment (9-03.11(1)) and 30% 4-inch cobbles (9-03.11(2)) to remain stable through the 100-year event. In addition to the proposed meander bars, 2-man habitat boulders (WSDOT spec 9-03.11(4)) placed at the leading edge of meander bars would also help preserve the meander planform of the stream.

A comparison of the observed, partially mobile D_{84}, and proposed streambed material GSDs is provided in Table 16. The resulting overall proposed design GSD in Table 16 reflects WSDOT's Streambed sediment mix as specified in the modified Shields stress worksheet. These GSDs also meet the Fuller-Thompson criterion for reducing subsurface flow potential.

Because actual mixes noted as meeting WSDOT specifications at pit sources can be highly variable in their composition, the streambed mix GSD should be verified by sieving at the source and adjusted as needed to reflect materials that are actually available at the time of construction.

Table 16: Observed, Calculated and Proposed Streambed Gradations

Sediment Size	Observed Reference Reach (in)	Calculated Partially Mobile Streambed (in)	Proposed Streambed (in)	Proposed Meander Bars (in)	
D_{16}	0.1	0.1	0.1	0.1	
D_{50}	0.2	0.5	0.6	1.0	
D_{84}	0.5	1.3	1.7	2.2	
D_{90}	0.7	1.6	1.9	2.6	
D_{MAX}	2.0	3.3	2.5	4.0	

5.2 Channel Complexity

To mimic the natural riverine environment and promote the formation of habitat, the design incorporated placement of key LWM pieces within and across the channel and floodplain. Placement will generally mimic tree fall found in the reach upstream and downstream of the crossing. Complexity is also provided by the alternating bar layout proposed in Section 4.4.

5.2.1 *Design Concept*

The total number of key pieces was determined in consideration of criteria presented in Fox and Bolton (2007) and Chapter 10 of the *Hydraulics Manual* (WSDOT 2019), in which WSDOT's recommended key piece density for the project site is 3.4 key pieces and 39.48 cubic yards of volume per 100 feet of channel. A key piece is defined as having a minimum volume of 1.31 cubic yards, which corresponds roughly to a 30 feet long log that has a diameter at breast height (DBH) of 15 inches. WSDOT has established a design goal for this project where the Fox and Bolton (2007) criteria are to be calculated for the total regrade reach length including the culvert, but the pieces of wood are to be distributed outside of the culvert. For the proposed total regrade length of 290 feet, the design criteria for this reach are ten key pieces with a total LWM volume of 114 cubic yards (Appendix H). In small streams, the volume criterion may not always be practically achieved without completely filling the channel and placing a sizeable amount of wood outside of the 2-year flood extent, where smaller diameter logs can achieve the same biological and geomorphic functions. In this design, the primary goal was to exceed the density criterion to get closer to or even meet the volume criterion, while not overloading the stream channel outside of the culvert. Where feasible, wood can be added outside of the regrade extent with the condition that heavy equipment not disturb the channel and floodplain significantly.

A conceptual LWM layout has been developed for the project reach based on site placement geometry, involving placement of twenty-two (22) loose, roughly 30 feet long logs with rootwads (Figure 57), which is more than double the number criterion for key pieces (Appendix H). There is space for this number of pieces, and it allows for smaller pieces of wood in the 15- to 20-inch DBH range, sizes that are comparable to other pieces of wood at the site and gives the contractor flexibility in sourcing wood. This increased number of pieces in turn facilitates getting closer to the net volume target, noting that criterion cannot be reached in this site without completely choking the channel with wood. The mobility and stabilization of LWM will be analyzed in later phases of design. The loose logs will have intact branches to the extent possible. Some will be placed entirely in the channel (Type 2), some will be placed with rootwad in the channel and tip on the floodplain/adjacent slope (Type 3), and some will span the bankfull channel to promote scouring underneath (Type 4). The type 3 and 4 designs will involve self-ballasting and interlocking with existing trees for stability. The type 2 log will be kept in place by other logs on top, and wedging between streambanks.

The LWM pieces will be placed so they provide habitat features for fish, form pools, and refuge habitat under high flow conditions. Wood stability and the need for anchoring will be assessed at the Final Hydraulic Design (FHD) level. Key pieces will be designed to be anchored by either suitable embedment length/depth, or interlocking with existing trees. To meet WSDOT's total LWM number target, twelve (12) additional 12" or larger DBH trees with rootwads would be needed. These smaller pieces would

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need to be placed loose as directed work, or designed to be embedded in the banks, integrated with the installation of key pieces.

Risk of fish stranding during summer flow conditions is minimal because proposed grading directs flow back to the main channel and does not promote isolated pools. Similar to a natural stream system, there is the potential for floodplain pools that create some potential to isolate fish that have entered during high flow events.
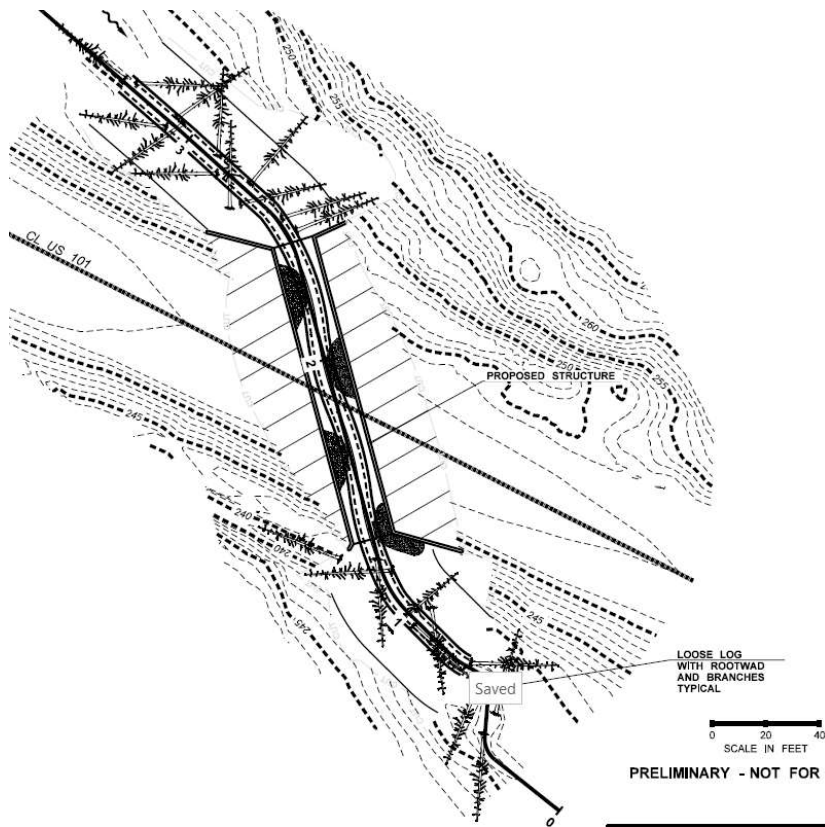
Figure 57: Conceptual layout of key LWM and alternating bars for habitat complexity
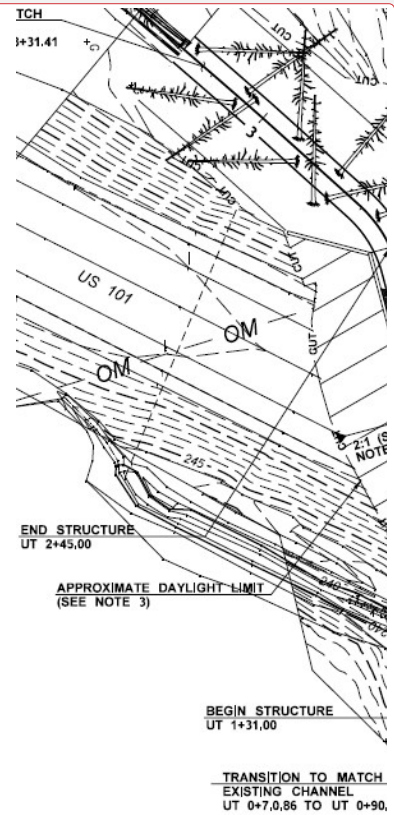
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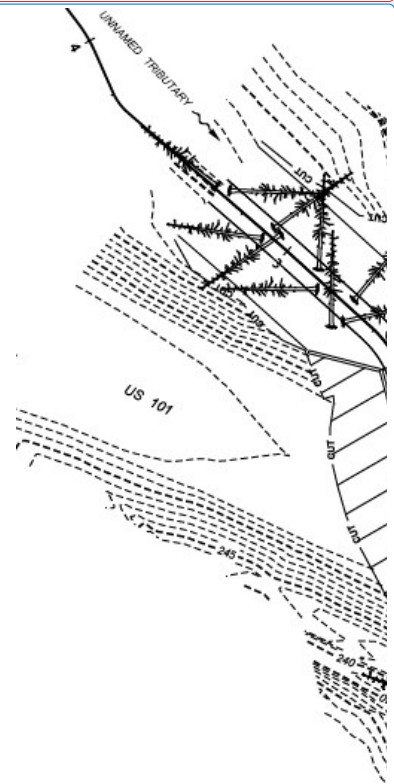
6   Floodplain Changes

This project is not within a mapped floodplain. The pre-project and expected post-project conditions were evaluated to determine whether there would be a change in water surface elevation and floodplain storage.

6.1   Floodplain Storage

Floodplain storage is anticipated to be affected by the proposed structure. The installation of a larger hydraulic opening will greatly reduce the amount of backwater and associated peak flow attenuation that was being caused by the smaller, existing culvert. A comparison of pre- and post-project peak flow events was not quantified as the models were run with a steady flow rate specified at the upstream boundary of the model. The elimination of attenuation upstream may result in an increased peak flow magnitude at the Larson Brothers Road stream crossing a short distance downstream.

6.2   Water Surface Elevations

Installation of the proposed structure would eliminate the backwater impacts just upstream of the existing culvert, resulting in a reduction in water surface elevation upstream. The water surface elevation is reduced by as much as 4.0 feet at the inlet of the existing culvert at the 100-year event, as shown in Figures 58 and 59. Figure 58 also depicts the extent of backwater that is eliminated.

Downstream of the outlet, the water surface elevation change varies between no change and less than a 0.1-foot rise from the existing to proposed conditions.

Figure 58: Existing- and proposed-conditions 100-year water surface profile comparison
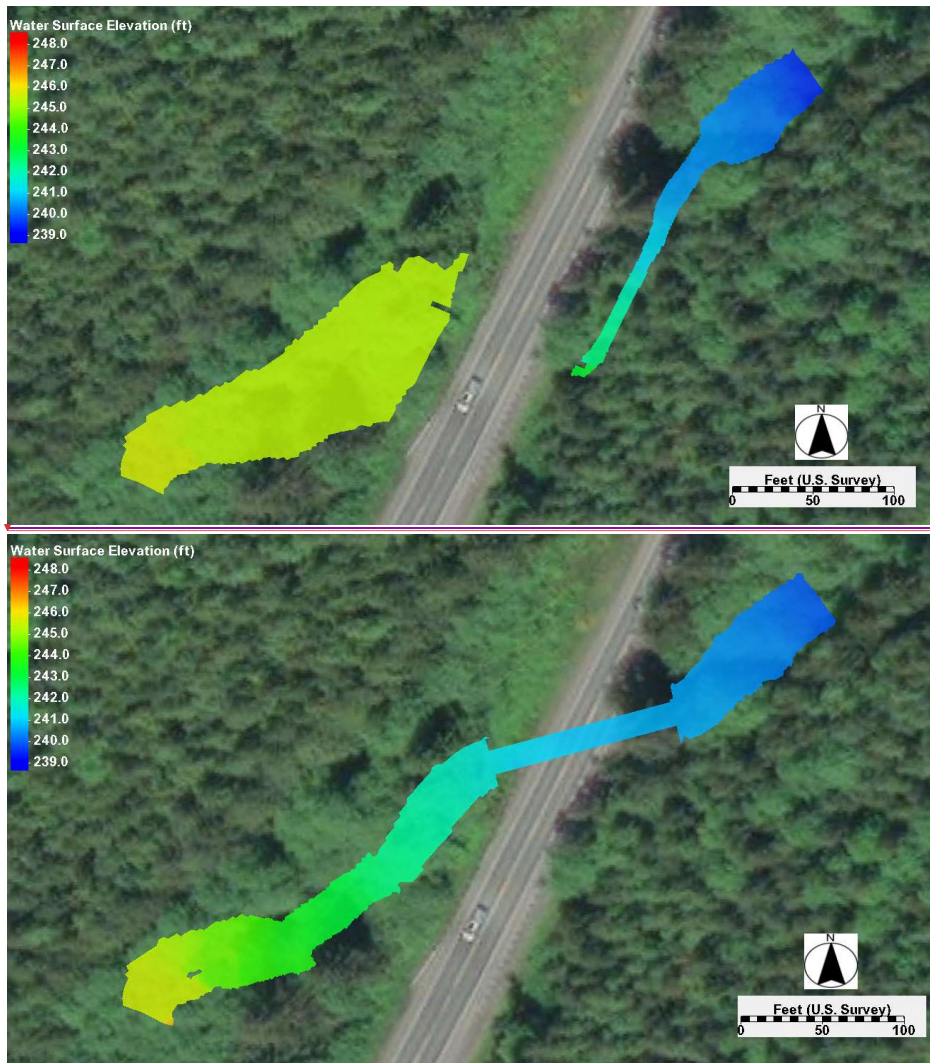
Figure 59: Water surface elevation change from existing (top) to proposed (bottom) conditions

7   Climate Resilience

WSDOT recognizes climate resilience as a component of the integrity of its structures and approaches the design of bridges and buried structures through a risk-based assessment. For bridges and buried

structures, the largest risk to the structures will come from increases in flow. The goal of fish passage projects is to maintain natural channel processes through the life of the structure and maintain passability for all expected life stages and species in a system. At a minimum, climate change is addressed in all bridge, buried structure, and fish passage projects by providing a design in which the foundations or bottoms are not exposed during the 500-year flow event due to long-term degradation or scour. WSDOT also completes a hydraulic model for all water crossings on fish-bearing streams, regardless of design methodology, to ensure that the new structure is appropriately sized. If the velocities through the structure differ greatly from those found elsewhere in the reach, the structure width may be increased above what is required by Equation 3.2 in the WCDG.

General climate change predictions for the broader region are for increased rainfall intensity during winter months, with the caveat that there is great spatial variability in the projections that may preclude downscaling to the project site drainage area, which is relatively small (WSDOT 2011). The project site crossing has been evaluated and determined to be a low-risk site based on the Climate Impacts Vulnerability Assessment maps (Figure 60). Based on the determination of this location being a low risk site, no additional climate change design modifications were made. The new structures were designed so their foundations do not become exposed during the 500-year flow event. Also, hydraulic modeling indicated that the flow through the replacement culvert is not predicted to become pressurized (i.e., no freeboard) during the 500-year event.

7.1 Climate Resilience Tools

WSDOT also evaluates crossings using the mean percent change in 100-year flood flows from the WDFW Future Projections for Climate-Adapted Culvert Design program. All sites consider the 2080 percent increase throughout the design of the structure. Appendix F contains the information received from WDFW for this site.

7.2 Hydrology

For each design WSDOT uses the best available science for assessing site hydrology. The predicted flows are analyzed in the hydraulic model and compared to field and survey indicators, maintenance history, and any other available information. Hydraulic engineering judgment is used to compare model results to system characteristics; if there is significant variation, then the hydrology is reevaluated to determine whether adjustments need to be made, including adding standard error to the regression equation, basin changes in size or use, etc.

In addition to using the best available science for current site hydrology, WSDOT is evaluating the structure at the 2080 predicted 100-year flow event to check for climate resilience. The design flow for the crossing is 59.6 cfs at the 100-year storm event. The projected increase for the 2080 flow rate is 16.5 percent, yielding a projected 2080 flow rate of 69.4 cfs.

7.3 Climate Resilience Summary

A minimum hydraulic opening of 13 feet and a minimum maintenance requirement clearance of 6 feet from the channel thalweg to the inside top of structure allows for extreme event flows to pass through the replacement structure safely under the projected 2080 100-year flow event. This will help to ensure

that the structure is resilient to climate change and the system is allowed to function naturally, including the passage of sediment, debris, and water in the future.
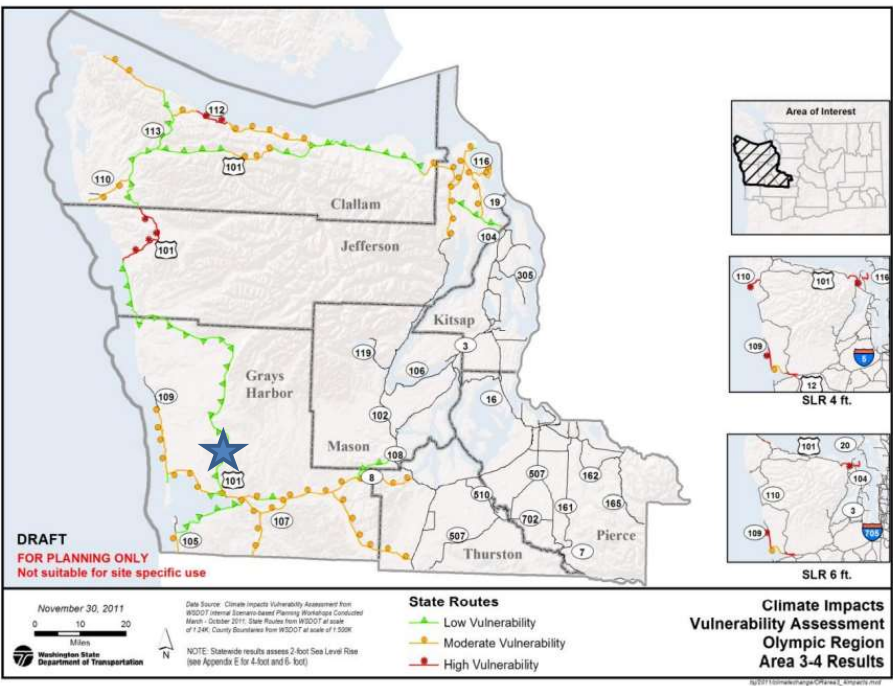
Figure 60: Climate impacts vulnerability assessment of Olympic Region areas 3 and 4 (source: WSDOT 2011). Site location is indicated by star

8   Scour Analysis

Total scour will be computed during later phases of the project using the 100-year, 500-year, and projected 2080 100-year flow events. The structure will be designed to account for the potential scour at the projected 2080 100-year flow events. For this phase of the project, the risk for lateral migration and potential for degradation are evaluated on a conceptual level. This information is considered preliminary and is not to be taken as a final recommendation in either case.

8.1.1 *Lateral Migration*

Based on the evaluation in section 2.8.5, the risk for lateral migration of the project stream is considered negligible.

8.2   Long-term Aggradation/Degradation of the Riverbed

Based on the evaluation in section 2.8.4, there is a little risk of long-term aggradation or degradation at the project site over the life of the replacement structure, largely because the design reconnects the upstream and downstream grades with negligible discontinuity inf the longitudinal profile.

8.3   Local Scour

Three types of scour will be evaluated at this site: bend scour upstream and downstream of the replacement culvert, inlet scour, and contraction scour. Initial scoping level calculations indicate the amount of local scour will likely be small, on the order of 1 feet. These forms of scour will be evaluated in greater depth after the stream channel design has been finalized. It is anticipated that bend scour will be negligible at this site given the realignment that is proposed. Large wood pieces placed in the channel will have preformed scour holes constructed prior to rootwad placement.

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Summary

Table 17 presents a summary of this PHD Report results.

Table 17: Report summary

Stream crossing category	Elements	Values	Report Location
Habitat gain	Total length	5,715'	2.7 Site Assessment
Bankfull width	Average BFW	8.0'	2.8.2 Channel Geometry
	Reference reach found?	Y	2.8.1 Reference Reach Selection
Channel slope/gradient	Existing crossing	0.7%	2.8.4 Vertical Channel Stability
	Reference reach	1.1%	2.8.2 Channel Geometry
	Proposed	0.8%	4.4.2 Channel Planform and Shape
Countersink	Proposed	FHD	4.7.3 Freeboard
	Added for climate resilience	FHD	4.7.3 Freeboard
Scour	Analysis	FHD	8 Scour Analysis
	Streambank protection/stabilization	FHD	8 Scour Analysis
Channel geometry	Existing	-	2.8.2 Channel Geometry
	Proposed	Realign	4.4.2 Channel Planform and Shape
Floodplain continuity	FEMA mapped floodplain	N	6 Floodplain Changes
	Lateral migration	N	2.8.5 Channel Migration
	Floodplain changes?	Y	6 Floodplain Changes
Freeboard	Proposed	2.0'	4.7.3 Freeboard
	Added for climate resilience	0'	4.7.3 Freeboard
	Additional recommended	0'	4.7.3 Freeboard
Maintenance clearance	Proposed	6.0'	4.7.3 Freeboard
Substrate	Existing	D_{50}=0.75"	2.8.3 Sediment
	Proposed	D_{50}=0.5"/1.0"	5.1 Bed Material
			The streambed design considered the local characteristic grain size distribution (GSD) of gravel collected in pebble counts, standard streambed stability calculations for the proposed channel longitudinal and cross-section profile grading, and requirements of WAC 220-660-190. Two grain size distributions will be developed during the FHD phase, one for the streambed mix, and the second for a cobble armor surface on

			the proposed meander bars within the replacement structure. In addition, large wood material is proposed to be placed on and over the streambed to provide instream habitat complexity and overhead cover for fish. These two elements of the design are described in separate sections below.
Hydraulic opening	Proposed	15.0'	4.7.2 Minimum Hydraulic Opening Width and Length
	Added for climate resilience	N	4.7.2 Minimum Hydraulic Opening Width and Length
Channel complexity	LWM	Y	5.2 Channel Complexity
	Meander bars	Y	4.4.2 Channel Planform and Shape
	Boulder clusters	MAYBE	5.2 Channel Complexity
	Mobile wood	N	5.2 Channel Complexity
Crossing length	Existing	103'	2.7.2.3 Floodplain
	Proposed	114'	4.7.2 Minimum Hydraulic Opening Width and Length
Floodplain utilization ratio	Flood-prone width	35'	4.4.1 Floodplain Utilization Ratio
	Average FUR upstream and downstream	4.4'	4.4.1 Floodplain Utilization Ratio
Hydrology/desi gn flows	Existing	Regress	3 Hydrology and Peak Flow Estimates
	Climate resilience	Yes	3 Hydrology and Peak Flow Estimates
Channel morphology	Existing	Stage 1	2.8.2 Channel Geometry
	Proposed	Stage 1	5.2 Channel Complexity
Channel degradation	Potential?	N	8.2 Long-term Aggradation/Degradation of the Riverbed
	Allowed?	Y	8.2 Long-term Aggradation/Degradation of the Riverbed
Structure type	Recommendation	N	4.7.1 Structure Type
	Type	NA	4.7.1 Structure Type

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Appendices

Appendix A: FEMA Floodplain Map

Appendix B: Hydraulic Field Report Form

Appendix C: SRH-2D Model Results

Appendix D: Streambed Material Sizing Calculations

Appendix E: Stream Plan Sheets, Profile, Details

Appendix F: Scour Calculations FHD ONLY (to be completed at FHD)

Appendix G: Manning's Calculations (not used)

Appendix H: Large Woody Material Calculations

Appendix I: Future Projections for Climate-Adapted Culvert Design

Appendix J: Co-Manager Comments on Draft PHD Report and Stream Team Responses

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This appendix was not used because it is only included for the FHD Report.

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